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THE PHYSIOGRAPHY OF THE RIO GRANDE VALLEY, NEW MEXICO, IN RELATION TO PUEBLO CULTURE

BY

EDGAR LEE HEWETT, JUNIUS HENDERSON,
AND WILFRED WILLIAM ROBBINS

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LETTER OF TRANSMITTAL

THE SCHOOL OF AMERICAN ARCHÆOLOGY,
Santa Fe, N. Mex., November 1, 1912.

DEAR SIR: I herewith transmit the manuscript and illustrations of a series of three papers under the general title "The Physiography of the Rio Grande Valley in Relation to Pueblo Culture," by Edgar L. Hewett, Junius Henderson, and W. W. Robbins. I am authorized by the managing committee of the School of American Archæology to offer this work for publication by the Bureau of American Ethnology as a part of the results of the coöperative work of the last two years between our respective institutions.

I am, very truly yours,

EDGAR L. HEWETT,
Director.

Mr. F. W. HODGE,
Ethnologist in Charge,
Bureau of American Ethnology,
Washington, D. C.

LETTER OF SUBMITTAL

SMITHSONIAN INSTITUTION,
BUREAU OF AMERICAN ETHNOLOGY,
Washington, D. C., November 8, 1912.

SIR: I have the honor to submit herewith a series of three papers relating to the physiography of the Rio Grande Valley, New Mexico as follows:

The Rio Grande Valley, by Edgar L. Hewett, Director of the School of American Archæology.

Geology and Topography, by Junius Henderson, Professor of Natural History and Curator of the Museum of the University of Colorado.

Climate and Evidence of Climatic Changes, by Junius Henderson and W. W. Robbins, Assistant Professor of Botany in the Agricultural College of Colorado.

These are designed to present a somewhat comprehensive view of the environment of the ancient tribes of the upper Rio Grande in New Mexico, especially of the Pajarito Plateau, and of the present Pueblo villages. They form a basis for several papers on the archeology and ethnology of the Rio Grande Valley which will present the results of research conducted jointly by the Bureau of American Ethnology and the School of American Archæology in 1910 and 1911. It is recommended that the present papers be published as a bulletin of this Bureau.

Very respectfully,

F. W. HODGE,
Ethnologist in Charge.

Hon. CHARLES D. WALCOTT,
Secretary, Smithsonian Institution.

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BY

EDGAR LEE HEWETT

THE RIO GRANDE VALLEY, NEW MEXICO

By Edgar Lee Hewett

PHYSIOGRAPHIC conditions are essentially correlative with facts of culture. Physical and psychic causes are to be held in the closest possible relation if we are correctly to interpret the intellectual remains of the native peoples of America, whether in the form of myth, ritual, and symbolism of plains and desert tribes or in architectural, sculptural, pictorial, and glyphic remains of the Mexican and Central American cultures. This briefly is the reason for beginning this series of studies on the archeology and ethnology of the Rio Grande valley with a discussion of the physiography of the region under investigation. These physical facts are presented in order that in a final synthesis of forces bearing on the culture history of the Rio Grande valley the student may have at hand wider knowledge of basic correlative conditions. The climate with its physical and psychic influences, the soil and its potentialities, the geologic structure of the country and its relation to the simplest problems of welfare, are all phenomena that must be reckoned within the study of man in the cultural process.

For such a study the Rio Grande valley affords exceptional facilities. It is an important part of a large and varied climatic province usually designated "the Southwest," in former times often spoken of as "the American Desert." Its climatic conditions are peculiarly definite, its geologic history is expressed clearly, and its physical structure strongly marked. The relation of such an environment to human activity in its physical aspects, as house-building, house life, and occupation, is obvious, while its influence on social organization, symbolic art, ritual, ceremony, all the phenomena of the religious life was, though less conspicuous, probably no less coercive. All the sources necessary to the study of human life in the valley during a long period are present. There are a wealth of well-preserved archeologic remains marking every stage of the pre-European epoch and much of similar character belonging to the period following the Spanish invasion. Living in the valley are Pueblo communities that have existed here for centuries, related to the ancient population in manner and degree not fully established, still conserving in myth, symbolic art, religious observance, and social order, the culture of the ancients. In addition to this there is yet to be recovered a wealth of documentary history of the period of Spanish conquest which is as essential to the completion of the record as is either of the lines

of information above mentioned. Local archives will yet yield much of value, as will also, in much larger degree, those of Mexico, but doubtless the chief source to which we must go is the Archivo General de las Indias in Spain.

Accordingly a series of papers will be presented dealing not only with the ancient monuments and excavations but also with the ethnology, documentary history, and physical geography of the region.

As yet the geographers and geologists have furnished no thorough studies of the Rio Grande valley. There are available the maps of the Wheeler Survey, which are substantially correct for leading topographic outlines, and early sheets of the United States Geological Survey, which are useful, though inferior to those of later issue covering other sections. The reconnoissance reports of the Macomb, Wheeler, and Hayden expeditions refer to the broader lines of geologic topography. In recent years the University of New Mexico has made important studies on the geologic history of the vicinity of Albuquerque.

The Rio Grande valley embraces the Pueblo region that belongs to the Atlantic side of the continental divide. The section here considered lies between 36° 30′ and 35° 15′ north latitude and between 105° 30′ and 106° 50′ west longitude; roughly, it is that portion of the Rio Grande valley which lies between Taos and Bernalillo, New Mexico, a distance, north and south, of 75 miles. This drainage area is approximately 75 miles wide. We are discussing then a section of country about 75 miles square, an area of about 3,600,000 acres. Physiographically it affords a satisfactory type-section of the Rio Grande basin. It embraces the principal foci of ancient population of the valley, and within its boundaries are villages representing all the surviving ethnic groups of the eastern Pueblos.

The Rio Grande enters this quadrangle in longitude 105° 45′ and leaves it at a point 50′ meridionally (approximately 50 miles) to the west. The general trend of the valley is thus from northeast to southwest. The fall during this course is from an altitude of 7,000 to one of 5,000 feet above sea level, this being accomplished by a gradual descent, no falls and no considerable rapids occurring at any place. At its point of entrance into this rectangle the bed of the river is in an impassable box canyon and so continues to Cieneguilla. Thence the canyon is still of great depth but permits of the passage of a wagon road. In the formation of this narrow canyon it has been necessary for the river to cut its channel through a wide-sweeping lava flow of great thickness, a phenomenon that is repeated at White Rock canyon, 20 miles below. At La Joya the Española valley opens out; this is 20 miles in length.

The leading geologic features of the Rio Grande valley are conspicuously expressed. One finds few areas in which the geologic topography seems particularly obscure. The general structure of the valley varies but little throughout the course herein described. The great synclinal trough, about 40 miles wide, lies between two imperfectly parallel mountain ranges. On the east is the Santa Fe range, which is a continuous chain, a prolongation of the Sangre de Cristo range of Colorado, embracing the highest peaks in New Mexico, some of which reach an altitude of 13,000 feet. On the west is the Jemez range, made up of a number of subranges and spurs locally known as the Tierra Amarilla, the Valles, the Gallinas, and the Nacimiento ranges. These mountains are characterized by broadly rounded contours with elevated valleys between the ranges. The highest peaks are in the neighborhood of 11,000 feet in altitude.

The river keeps toward the western side of the trough. On each side is a narrow strip of highly productive irrigable bottom land, well adapted to raising grain and fruit and to gardening. On the west side this strip is only a few hundred yards wide, being closely limited by the abrupt escarpments of the Pajarito plateau, which lies between the river and the foothills of the Jemez range. The main flood plain, only a mile or two wide, is on the east side. This is limited by an expanse of broken country about 20 miles in width extending back to the Santa Fe range. This strip is characterized in part by naked arenaceous bluffs, which in places are eroded into weird castellated bastions, and in part by rounded gravel-covered hills. The naked Tertiary sands of this valley are nonproductive, and large areas are so situated that they will always be in a state of denudation. There are occasional threads of fertility along the meager watercourses, and in places the bench lands have undergone a degree of aggradation by reason of the distribution of material from adjacent mountain sides; this has resulted in a covering of moderately fertile gravel and silt, which supports a fair amount of grass and other vegetation. Extensive fluviatile deposits nearer the river indicate the existence at some former time of a much greater river than the present Rio Grande. Evidence pointing in this direction is repeated and emphasized in the course of the Rio Grande after its emergence from White Rock canyon opposite Santa Fe.

At the lower end of the Española valley, just below San Ildefonso, the river enters the canyon, cutting its channel through another wide-sweeping lava flow. For a distance of two or three miles the railway follows the bank of the river down this canyon, which for the next 20 miles is passable only by an Indian trail, even this having to leave the canyon toward the lower end and pass out over the mesas. The canyon ends just above the Indian village of Cochiti; thence the flood plain is larger and still on the east side of the river.

The volcanic mesas still hug the river on the west, while to the east of the flood plain the areas of naked marl are small and the area of gravel and silt-covered hills and mesas is of greater extent.

The most striking section of the entire region herein described is that bordering the Rio Grande on the west between the Chama river and Cochiti. No other section in the Southwest has played a more conspicuous part in human history. It became the principal focus of ancient culture in the Rio Grande drainage, and its peculiar geologic structure powerfully influenced the aboriginal culture of the entire Southwest, particularly in the domain of house life. It is the eastern half of the elevated plateau upon which are superimposed the Jemez mountains; to this has been given the name Pajarito plateau. Its original uplift accompanied the formation of the Jemez range, but important changes have since taken place. The most important of those was the laying down of a vast sheet of volcanic tufa of a maximum thickness of perhaps 1,500 feet, which at one time completely covered the plateau but which has since been rent, sculptured, and dissected by water and wind into the weirdly beautiful condition that it now presents. In the northern part hardly more than ten per cent of the original cap is left in place, the remaining fragments standing out boldly from the foot of the mountains as circular or elongated geologic islands. These sometimes take the form of narrow tongues, several miles in length and from a few feet to half a mile in width. Between are lightly timbered valleys and dry arroyos. In this northern part, which is called the Puyé district, from its principal focus of ancient habitation, the tufa cap has been entirely removed for a distance of several miles back from the Rio Grande, being superseded by a level grassy plain. Farther south the tufa cap approaches the river, and southward from the point at which the Denver and Rio Grande railway crosses the Rio Grande near San Ildefonso the massive yellow bluffs appear hundreds of feet above the river as the upper stratum, overlying the recent basaltic extrusions. Thence southward from fifty to seventy five per cent of the tufa sheet remains in place, and instead of presenting the appearance of a large number of geologic islands, resting upon a common level, as farther north, there is more the appearance of a level plateau rent by thousands of canyons which sink below the general level to a depth of from 50 to 700 or 800 feet. Above White Rock canyon the eastern rim of the plateau is broken into detached masses, which stand out as huge isolated bastions, while farther south a continuous rim is presented toward the river, broken only by the entrance of the side canyons. In the region contiguous to the Rio Grande, lying between the Guages and the Pajarito, are many fine examples of basaltic gorges. This section was the focus of the recent volcanic activity, which here produced some of the most

striking scenery from the geologic point of view to be found in the Southwest.

In most places the color of the tufa blanket ranges from yellow to gray, varying with the exposure. In the neighborhood of the basaltic contact, areas of dark brown occur and in some places patches of almost pure white ash are to be seen. The greater part of the formation, the material of which originated in the cones of the Jemez mountains to the west, seems to have been laid down somewhat uniformly as a rather coarse ash, nowhere approaching commercial pumice, usually much mixed with spicules of silica. The formation presents every degree of compactness—the light gray ash that can be removed with a shovel, somewhat harder porous masses in which are thousands of natural caves formed by wind erosion (the advantages of which for shelter constituted probably one of the first inducements for the peopling of the region), and finally the fairly compact unbroken strata hundreds of feet thick, as seen in the canyon walls at the Rito de los Frijoles, the North Alamo, and the Puyé. The soft honeycombed formations afforded, with but little additional excavation, dwellings for the first inhabitants, while the more compact masses furnished the light building stone for the great community houses of more recent times that were built upon the mesa tops, in the valleys, and on the talus against the massive walls, as at the sites above mentioned.

Many formations of unusual character are found here and there, giving variety and character to the scenery. Such are the mud flows which occur as brownish stratified masses, and the remarkable tent-shaped rocks, of which the finest examples are at Otowi, but which occur also at many other places (pl. 8–10). Those at Otowi are especially noted for having been used as human habitations. They are to be seen in all stages of formation—the porous stratum in which they originate still covered with the cap of more compact tufa, the detached masses with fragments of the cap as balanced rock remaining upon the apex, and the completely isolated finished cones. A whole village of these is to be seen in Otowi canyon.

Two natural caverns of considerable size are found in the southern part of the plateau, one in the Rito de los Frijoles and one in the Cañada de la Cuesta Colorada. Both were utilized by the inhabitants for ceremonial purposes. This portion of the plateau embraces the most stupendous canyons, the wildest scenery, and affords the grandest panoramas to be seen in New Mexico, and in fact scenes that can scarcely be paralleled anywhere.

The principal eastern tributaries of the Rio Grande are Taos, Santa Cruz, Pojoaque, Santa Fe, and Galisteo creeks, small streams with narrow flood plains. All of these usually carry a small amount of

water to the confluence during a considerable part of the year. On the western side there is one important tributary, the Rio Chama, a large river, rising in southwestern Colorado. A description of its basin in its lower course would be almost a repetition of that of the Rio Grande. Its right bank is bordered closely by the volcanic escarpments of the Pajarito plateau, and on the left a narrow fertile flood plain is immediately superseded by an extensive valley filled with the picturesque hills of Pliocene sands. The Santa Clara, Guages, Pajarito, Bravo, Rito de los Frijoles, Alamo, Colorado, and Cochiti are small creeks perennial in their upper courses, but none of them, with the exception of the Rito de los Frijoles, carries its water to the Rio Grande except in flood seasons.

Of the area under consideration, 75 miles square, probably five per cent is irrigable agricultural land of great fertility. Forty-five per cent is barren irreclaimable marls, lava flows, and sand hills, and fifty per cent may be classed as mountain land more or less forested. The forested land at present is only moderately valuable for pasturage and lumbering, but is susceptible of improvement in these respects under scientific forest management. This portion of the drainage area has an important function in the conservation and distribution of surface waters. Progressive deterioration in its forest conditions would be accompanied by a corresponding decline in agriculture in the entire region that depends on the Rio Grande for irrigation water, while any sudden and extensive forest destruction would lead to catastrophic results, rendering the region uninhabitable. Of the present forested area the greater part is only indifferently wooded, not more than a quarter of the timber being of merchantable quality. Probably half of this area could be classed as light woodland and the remaining quarter as scrub. The well-forested portions of the rectangle are, (1) the Santa Fe mountains area, including the entire eastern side of the basin; (2) the Placer and Sandia mountains area, a small section in the south-central part; and (3) the Jemez plateau, the region lying west of the Rio Grande and north of the latitude of Santa Fe. Extensive fires have denuded many of the rounded tops of these mountains, giving the impression that these peaks extend above the timber line.

Meteorological conditions throughout this region are peculiarly definite. There is a high percentage of cloudless weather, a rare transparent atmosphere, light precipitation, rapid evaporation, low humidity, and considerable wind, especially in the spring. Vegetation dries up rather than decays; meat cures in the open air without salt. In the lower valleys the total precipitation ranges from 10 to 15 inches annually, very little being in the form of snow. In higher altitudes this is increased to from 15 to 20 inches, with a considerable amount of snow. There is occasionally an exceptional year when

precipitation reaches 25 inches in the higher mountains. Precipitation is unequally distributed throughout the year. Heavy rainfalls of a few hours' to some days' duration are followed by months devoid of moisture. The effects of rainfall disappear rapidly because of the character of the soil and the atmosphere. The range of temperature is considerable, owing to the great range in altitude. The nights are invariably cool, even in summer. There is little zero weather in winter except in the high altitudes, and oppressive days in summer are unknown even in the lower valleys. This is due not so much to absence of heat (for at midday there may be a scorching temperature) as to lack of humidity. Sultry, muggy days are unknown. The season for crops varies in length with the altitude, but is rather short at best. Small grain thrives even in the highest valleys, while fruit-growing is limited to areas below 7,000 feet. Various grasses flourish up to the highest altitudes. Corn matures in the valleys and on the mesas up to 8,000 feet. This crop, while an exceedingly meager one in comparison with the prolific yield of the Middle West, has been very influential in determining the aboriginal culture that developed here.

The country is poor in natural food products. In the canyons a few berries, wild cherries, and wild plums are found. Certain species of oak furnish acorns in quantities sufficient for food, and the nuts of the piñon (*Pinus edulis*) are used by the Indians and Mexicans. There are some food fish in the Rio Grande and trout in the mountain streams, but the Pueblo Indians fish but little. Game is scarce. Deer are more rare than in the northern part of New England. Bears are occasionally found in the mountain canyons. Coyotes, timber wolves, wildcats, pumas (mountain lions), and squirrels exist, but not in large numbers. There are some wild turkeys in the forests, but in general birds are rare. The rattlesnake is the only reptile that is numerous, and this in only a few places, notably in the White Rock canyon between Buckman station and the mouth of the Rito de los Frijoles. In marked contrast to the poverty of vertebrate life is the extreme richness of the insect fauna. At certain seasons butterflies appear in the valleys in vast numbers. There are many species of wild bees. Occasionally swarms of locusts appear and these are greatly prized by the Pueblo Indians for food. Tarantulas and centipedes occur, but not so plentifully as on the plains east of the Rocky mountains. There are lizards in almost endless variety, and great numbers of bats frequent the ancient cliff houses of the plateau area.

The method of mesa building seen in the Rio Grande valley points to a former climatic condition radically different from that which now prevails in the Southwest. The sudden heavy downpour of rain now characteristic of this region sweeps large quantities of gravel and silt from the mountain sides into the gulches and on into the river basins,

creating a formidable obstacle to irrigation projects in the rapid filling up of reservoirs. This condition does not permit of uniform distribution of the soil from the mountain sides over the lower mesas and bench lands, such as obviously took place in earlier times. A humid climate, characterized by much rainfall in steady, long-continued showers, would cause a constant gradual degradation of higher slopes and redistribution of the material upon the lower bench lands in the uniform manner here seen. Furthermore, the Rio Grande and many smaller streams show evidence of volume formerly much greater than at present.

The climate of the Southwest may have been at one time similar to that of Mexico in the high altitudes. No reason exists for believing that any great physical catastrophe occurred to change conditions. There is evidence of seismic activity but of not excessive violence. This is seen in such shallow canyons as the Pajarito, where enormous bowlders, fragments of the tufa escarpments, have been projected to so great a distance from the cliff onto the level flood plains that it is necessary to assume some initial force other than the mere breaking away of the rock masses in the natural course of weathering. There are evidences that the country has undergone a slow progressive desiccation, extending over a long period of time. That the epoch of human occupancy of this region extends back into the period of greater humidity seems probable. Agriculture, without irrigation, has flourished on considerable areas of the Pajarito plateau that are now nonproductive from lack of water. That plateau anciently supported a large agricultural population where now it supports none. On areas like Mesa del Pajarito, where the aggradation of a hundred years under present climatic conditions would be almost imperceptible, where in fact no distribution of soil from higher levels is now in progress, there has been upbuilding of the general mesa level about the walls of ancient buildings to an extent that is not explicable under present conditions. The structures here referred to are not the large community houses, but of an older scattered "small-house" type, the predecessor of the many-chambered pueblo.

While it thus seems probable that man witnessed these climatic changes, the age to which we would have to return to find a condition so different from the present can be fixed only within certain geologic limits. The gravels above referred to are considered late Pleistocene; that they are post-Tertiary is certain. In places they are found overlying the lava flows, and no instances have come to the writer's knowledge in which the reverse of this is the case. This makes necessary consideration of the question of the age of the New Mexico basalts. On this is here quoted Prof. R. T. Hill:[1]

[1] In *Bulletin of the Geological Society of America*, III, p. 100.

It is also evident from the investigations that eruptive activity has occurred in the Texas-New Mexican region from Cretaceous to the present time, and at least three well-defined epochs are at present recognizable which may serve as a guide to future observations, viz:

1. The Austin-Del Rio system, or Schumard knobs; ancient volcanic necks or laccolites bordering the Rio Grande embayment, begun in later Cretaceous time, the lava sheets of which have been obliterated by erosion.

2. The lava flows of the Raton system, which are fissure eruptions of Tertiary time, and which are only partially removed by erosion.

3. The cinder cones and lava flows of the Capulin system, which are late Pleistocene, and which still maintain their original slope and extent.

This question was made the subject of investigation by the late Prof. C. L. Herrick, whose geological interpretations, it need hardly be said, command high respect. He says: [1]

Much time has been expended in the effort to determine the precise age of these basalt sheets and the results seem to be unambiguous. The fact that these lavas flow over the bases of the trachyte and rhyolite mountains and flows, as at Socorro, and burst through and are interbedded in the tufa sheets as at Cochiti district, shows the basalt period to follow the trachyte period of eruptive activity. Direct superposition on the Tertiary sands in numerous places indicates their Post-tertiary age. Often the Tertiary strata are much altered and reddened by the contact, being baked and indurated in those places where the flow was thickest but less altered by the thinner portions of the sheets. The question as to the period that may have elapsed since these flows is more difficult of solution. We have so far failed to find an instance where the lava has flowed over the river deposits of supposed Pleistocene age. . . . It has been repeatedly stated that these lavas are of recent date and that they cover remains of human industry. So far as this portion of the territory is concerned this may be emphatically denied. Specimens of maize embedded in what was presumed to be lava have been displayed in proof of the statement that man existed prior to these lavas. It is not denied that recent igneous flows have occurred in various parts of the West, but it seems very improbable that even the latest of these basalts could have been cotemporaneous with man in New Mexico. An analysis made by Mr. D. W. Johnson of the so-called lava containing corn proved it to be highly acid and to have a composition impossible for basalt or an ordinary slag.

There have come into the hands of the writer specimens of charred corn imbedded in so-called "lava" from four sites in the Rio Grande drainage and one in the San Juan. Two of these specimens came probably from the sites examined by Doctor Herrick, namely, the Jemez valley below Jemez pueblo and the Cañada de Cochiti. The writer's examination of these confirms his results. Analysis of one specimen obtained from the Santa Fe valley and of another from the Chama valley disclosed the fact that the material bears no chemical relation to basalt, being an acid product often resulting accidentally by the action of fire on ordinary adobe soil. The specimens present superficially the appearance of true lava.

There is as yet no evidence that there was human occupancy anterior to or contemporaneous with the New Mexico lava flows, though these are, geologically speaking, of recent occurrence, possibly not

[1] In *Bulletin of the Scientific Laboratories of Denison University*, XI, p. 180.

more than 8,000 to 10,000 years old, and there is no reason for limiting the age of man in the Southwest to the last few centuries.

It would be premature to discuss at this time the bearing of the facts of physiography here noted on the facts of culture history to be presented in subsequent papers. It may be suggested, however, that the evidences now at hand indicate that the original culture that arose in the Rio Grande valley was not wholly or mainly dependent on irrigation but that in course of time it became so. Aridity, therefore, was not originally the dominant factor in shaping the culture of the Southwest. It came to be so ultimately, and in such manner that adaptation to the changing conditions was possible. The aridian culture of the Southwest is the result of gradual adaptation.

In the following paper Professor Henderson presents in detail the results of his study, in the summer of 1910, of the geology and topography of a limited area of the region under consideration, his observations having been made mainly on the Rito de los Frijoles and its vicinity. In the next paper the same writer, in collaboration with Professor Robbins, brings together, under the title "Climate and Evidence of Climatic Changes," the evidences and views that have been set forth touching the important question of possible modifications of climate in the Southwest.

GEOLOGY AND TOPOGRAPHY OF THE RIO GRANDE REGION IN NEW MEXICO

BY

JUNIUS HENDERSON

CANYON OF EL RITO DE LOS FRIJOLES, SHOWING VERTICAL TUFA BLUFF ON THE NORTHERN SIDE AND THE GENERAL SLOPE OF THE MESA TO THE SOUTHEAST

GEOLOGY AND TOPOGRAPHY OF THE RIO GRANDE REGION IN NEW MEXICO[1]

By Junius Henderson

In the present age of railways and machinery the location of new villages, towns, and cities is controlled to a much greater extent than formerly by transportation lines and the proximity of products of commercial value. Cities may now be readily built in inhospitable deserts or other unfavorable localities where there are no good building materials, food products, or surface water, the former two being transported from great distances by railways and the latter being obtained from deep wells made possible by boring machinery or piped from remote sources. In more primitive times, when the proximity of a suitable water supply, tillable lands, and building materials was necessary and ease of defense was important, geologic phenomena and topographic features were leading factors in the location of permanent habitations. The flow of water from permanent springs or perennial streams, easily defended cliffs or canyons, drainage, and lands suitable for agriculture are the direct results of geologic processes. Even the climate and the natural distribution and abundance of wild animals and native plants, which may form part of the food of a village population, are directly or indirectly influenced by geology and topography. Hence a study of these features in a region such as the one under consideration is necessary to a full comprehension of the environment and culture of its ancient inhabitants.

El Rito de los Frijoles, where the studies embodied in the present report were chiefly carried on, is a small rivulet flowing through one of the many canyons that dissect the Jemez plateau on the western side of the Rio Grande, north of west from Santa Fe, New Mexico. It is taken as a typical canyon of the region.

The general region is the Rio Grande basin in northern New Mexico, a broad valley lying between the Santa Fe mountains, which form the southward extension of the Sangre de Cristo range, and the Jemez mountains, which form the southward extension of the San Juan range. These two ranges well to the north in Colorado are composed of very high peaks, but in passing southward into New Mexico they

[1] See Bandelier, A. F., Final Report of Investigations Among the Indians of the Southwestern United States, *Papers Archæol. Inst. Amer., Amer. ser.*, IV, 139–41, 1892; Hewett, Edgar L., The Excavations at Tyuonyi, New Mexico, in 1908, in *Amer. Anthr.*, XI, 434–55, 1909 (*Papers School Amer. Archæol.*, no. 5).

drop to lower altitudes and finally merge into the general level of the region.

The western portion of the basin is part of the Jemez plateau, which includes the Jemez mountains and is bounded on the west by the Rio Puerco and on the east by the Rio Grande, extending from the northern line of New Mexico to about west of Santa Fe. The portion of the Jemez plateau lying between the Jemez mountains and the Rio Grande is called the Pajarito plateau. The Rito de los Frijoles is in the southern part of the Pajarito plateau. Approximately parallel canyons extending from east to southeast divide the plateau into a number of mesas, which slope rather gently from the mountains to the rim of the Rio Grande canyon.

Standing on any high point just west of Santa Fe, one may gain a clear conception of the larger features of the topography—the broad basin lying between two mountain ranges, the country sloping somewhat regularly from the bases of the mountains on each side to the river. In traveling over the region these larger features of the landscape may often seem, to one not thoroughly familiar with them, swallowed up or obscured by the magnitude and abruptness of the topographic forms in the immediate vicinity of the observer, so that the final impression is that of a confused network of deep, narrow lateral canyons and rugged buttes. To understand the region, one must ever keep in mind the idea that here were originally gentle, uniform slopes, which have been deeply gashed by canyons cut by running water.

In traveling up the valley from Santa Fe to Taos, on the east side of the Rio Grande, Carboniferous formations with low westerly dips are found along the flanks of the mountains, exposed by the wearing away of the overlying "marls". Doubtless the Carboniferous rocks and probably later formations are spread across the valley beneath the mantle of Tertiary sedimentary formations which are usually exposed where not covered by tufa and basalt. It seems probable that the outlines of this valley were established as a synclinal fold long before the mid-Tertiary deposition period, but the altitude of the mountains then is a matter of conjecture only. The exposed strata show that these Tertiary sediments were deposited in the valley to a depth of 1,200 to 1,500 feet, according to Hayden, but it seems likely that he included some Quaternary strata with the Tertiary. "The upper portions are yellow and cream-colored sandstones, sands, and marls. Lower down are some gray coarse sand beds with layers of sandstone."[1] These beds have since been deeply cut by stream erosion, the Rio Grande having excavated a deep valley, including the great valley of Taos. The formation has been

[1] Hayden, F. V., Geological Report, (*3d Ann.*) *Prelim. Field Rep. U. S. Geol. Surv. Colo. and New Mex. for 1869*, pp. 7–99, 1869; *1st, 2d, and 3d Ann. Reps. U. S. Geol. Surv. Terr. for 1867, 1868, 1869*, pp. 109–99, 1873.

A. PAJARITO PLATEAU AT EL RITO DE LOS FRIJOLES, JEMEZ MOUNTAINS IN THE BACKGROUND

B. RIO GRANDE CANYON BELOW EL RITO DE LOS FRIJOLES, CUT INTO BASALT, THE BASALT-TUFA CONTACT SHOWING ON THE RIGHT

large area. This material was doubtless ejected from a volcanic vent or vents, whether as mud or as "ashes" may be questionable. At the Rito de los Frijoles the deposit is 500 to 600 feet or more in depth. The exact conditions under which it was deposited are not easy to determine. In fact, in the great area covered by the tufa conditions would be almost certain to differ in different localities. Furthermore, it is not at all likely that the material was all ejected during a single eruption, and some of it may have been ejected in one condition and other portions in a quite different condition. Wherever the writer had opportunity to examine it, the upper part was very much like the lower part in constitution, but differed uniformly in being of somewhat greater specific gravity, hardness, and color, a matter which is discussed farther on. The high vertical cliff at the Rito gives one the impression that perhaps the whole softer, more homogeneous portion below may have been the result of one period of deposition and that the upper half or so of the formation, with its alternating hard and soft zones, may represent another period, yet the absence of any unconformity in material so easily eroded makes it difficult to believe this to be the case, unless the interdeposition period were very short indeed, or the slopes were so gentle as to permit only the most sluggish movement of surface waters.

Popular opinion in the region regards the formation as volcanic ash or volcanic mud deposited in a large body of water. Speaking of portions of the basin not examined by the author, some scientific writers have expressed the same opinion. At the Rito de los Frijoles the character of the material does not seem consistent with that view. It would be rash to express any definite opinion applicable to the whole region without examining the area in detail. The ground mass at the Rito is light, but variable in specific gravity, some fragments almost floating when placed in water. Especially is this true of the numerous pumice fragments, some of them several inches in diameter. These are scattered in great numbers throughout the formation from base to top, mingled with coarse, angular fragments of heavy rock, including obsidian. It does not seem at all likely that such material, differing so greatly in specific gravity and size, could have been deposited in a large body of water without a considerable degree of assortment, yet a search along the canyon walls at the Rito failed to disclose any definite evidence of the assortive action of water. At one place in Alamo canyon a small local deposit of stream-assorted tufa pebbles was found, just such as would be expected in places if deposition had been subaerial, whether by successive showers of volcanic ashes or flows of volcanic mud. It does not seem probable that the formation is the result of a single eruption. Between eruptions some erosion and redeposition of material would occur,

A. LOWER PART OF EL RITO DE LOS FRIJOLES CANYON, CUT INTO BASALT, THE BASALT-TUFA CONTACT ON SOUTHERN SIDE OF THE CANYON SHOWING ON THE RIGHT

B. BASALT-TUFA CONTACT ON THE NORTHERN SIDE OF THE LOWER PART OF EL RITO DE LOS FRIJOLES CANYON, OPPOSITE *A*

even though the inter-eruption periods were of short duration, for the waters of the Rio Grande and other streams must have continued to flow somewhere in the basin affected by the tufa. The banding of the upper part of the tufa is not easy to understand. If the bands signify successive deposits, there should be marked unevenness in evidence of local erosion between the bands, which the writer has failed to find. If the deposition occurred in a large body of water of sufficient depth to avoid wave erosion, that fact might account for this point. The extent of this banding, evidenced by the bluffs and terraces hereinafter discussed, makes it evident that any such body of water must have been of great length, 30 or 40 miles in width and at least 1,000 feet in depth. If any barrier has been found which would account for such a body of water the writer has not learned of it. This and the lack of assortment of the material constitute very strong, though possibly not conclusive, evidence against the idea of deposition in water. On the whole, the impression derived from an examination of the tufa is that it consists of a series of flows of rather thin mud, inclosing the fragments of pumice, obsidian, and other rocks, though before this suggestion is accepted as final much more work should be done.

The tufa contains innumerable quartz crystals one to three millimeters in diameter. In weathering, the soft, fine material in many places is washed from the quartz crystals, leaving small deposits of clear crystalline quartz sand in the beds of gullies. Many ant hills two or three feet in diameter are composed almost entirely of the crystals; they are often seen glistening brightly in the sunlight. A careful examination of the weathered-out crystals in most cases shows that the facets are clear, bright, and sharp, but one side is usually broken away. It is quite probable that this is due to diurnal expansion and contraction, as the heat of the sun at midday is intense, while the nights are cool. The diurnal changes in temperature are not so effective in the disintegration of the tufa as in case of some other rocks, because it is somewhat elastic, so that the scaling off so noticeable in some of the granites and sandstones under such circumstances is not noticed here.

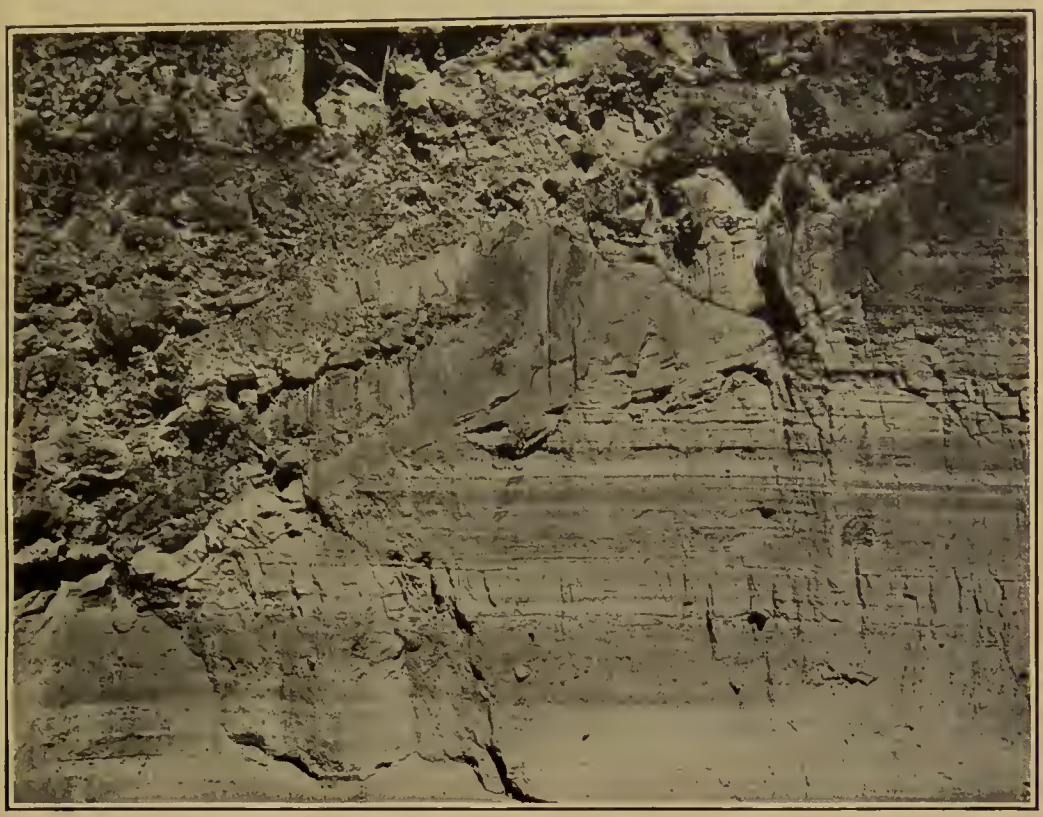
The quartz crystals fail to explain the origin of the tufa. It is believed that they were formed in the magma by its partial crystallization before it was ejected, and they would occur in their present condition probably whether the tufa were ejected in the form of ashes or of mud. The same sort of material may form volcanic ash or volcanic mud, according to the conditions under which its expulsion occurs. If violently ejected in a somewhat dry condition by an explosion it forms what is called volcanic ash, but if exuded in a thoroughly wet condition it comes out, of course, as mud.

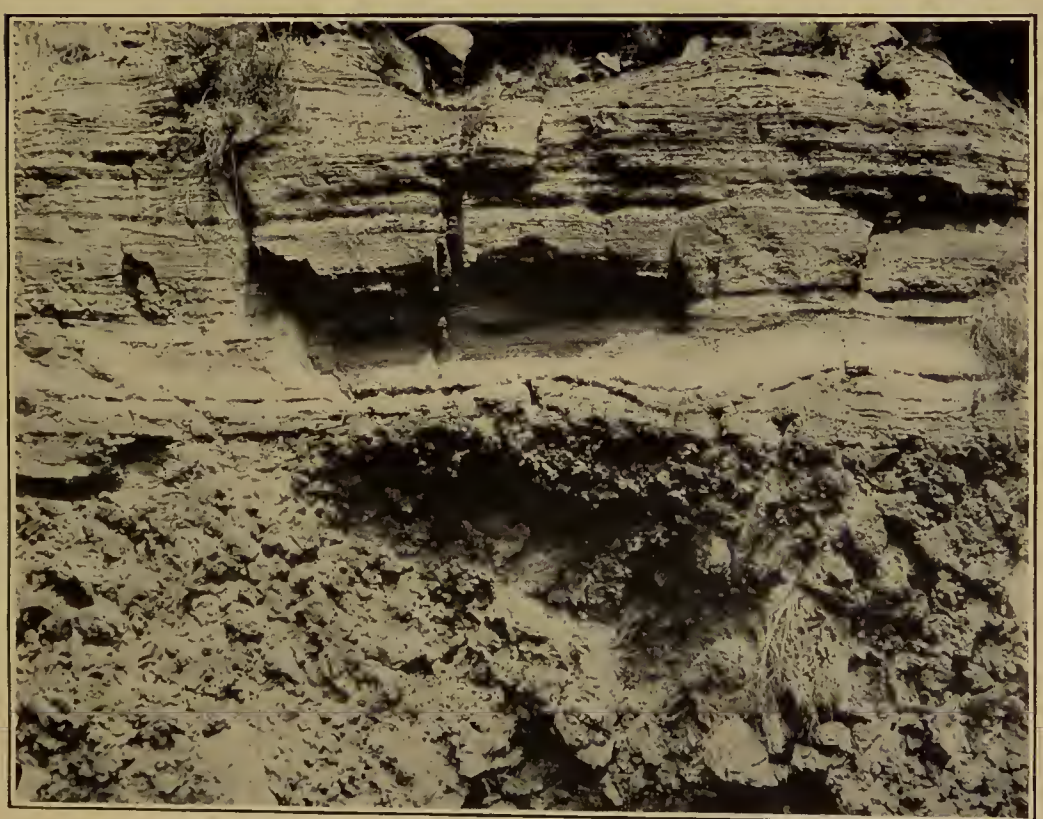
In the northern and western part of New Mexico are many old volcanic vents, and it is likely that the tuffs of the Pajarito plateau came not from a single vent, but from a number of vents about the rim of the basin, a suggestion long ago made, the confirmation of which time did not permit in the present work.

In the vicinity of El Rito de los Frijoles the upper half of the tufa-sheet is heavier, harder, and mostly of darker color than the lower half. Furthermore, some zones in the upper half are harder than others, while the lower half is more uniform in this respect. This difference in hardness is very important in connection with the cliffs and terraces hereinafter discussed. Throughout the formation the portions fully exposed to the weather are covered with a thin, ill-defined, somewhat hardened layer one-eighth to one-half inch in thickness, which protects it from more rapid weathering. The hard zones in the upper half are partly, if not wholly, due to a similar process of "case-hardening." In some vertical cleavage planes this hardening was found to have occurred on both sides of the minute crevices. In view of these facts the whole aspect of the cliff points to the likelihood that the hardening has been caused by water following in the one case vertical cleavage planes, in the other horizontal planes which may possibly represent the lines separating the ashes or mud of successive showers or flows.

As the upper part of the Santa Fe marls is considered early Pliocene, these overlying tuffs must be of later Pliocene or post-Pliocene age.

In many places intrusive basalts have been injected into or through the Santa Fe formation and the tufa. An excellent place to study the relation of the sedimentaries, the tufa, and the basalt, is in the vicinity of Buckman, at the crossing of the Rio Grande on the present road from Santa Fe to El Rito de los Frijoles. The intrusive character of the basalt is well shown, however, in Frijoles canyon, just above its mouth. There vertical contacts of masses of basalt with both sandstones and tufa are found well exposed, and horizontal sheets of basalt extend off into the tufa and between strata of sandstone. The basalt is hard and heavy, varying on weathered surfaces from light gray to black and covered in many places with superficial cavities up to half an inch in diameter, from the leaching out of some of the mineral constituents. It represents probably more than one flow. Nearly all of the basalt is in the olivine group. The first exposure in descending the canyon of El Rito de los Frijoles, however, is a sheet of very dense, fine-grained basalt which should probably be classed as a glassy basalt, showing in a gully on the northern side, half a mile or more above the upper falls. This dense material appears to be that which has been used in the manufacture of the "clinking stones" found in the old ruins of the canyon, and which were probably used





CONTACTS OF SANDSTONE AND BASALT, WHERE THE BASALT IS INTRUDED INTO THE SANDSTONE, LOWER PART OF EL RITO DE LOS FRIJOLES CANYON

by the ancient inhabitants for ceremonial purposes. It varies considerably in "ringing" qualities. The other basalts were used largely in the manufacture of metates and other artifacts. That there are older basalts in the vicinity is shown by the occurrence here, in the sandstones and conglomerates, of angular fragments of basalt up to at least six inches in diameter. The older basalt was not recognized in situ. At the lower falls is an exposure of the brown and yellowish-brown sandstone and conglomerate about 75 feet thick, with the angular basalt pebbles scattered throughout, but larger and more numerous in the upper 25 feet. No definite evidence of the age of the sedimentaries at this point is available, but they are surely older than the tufa and the basalt in contact with them, and antedate the cutting of the canyon, yet they are not thoroughly consolidated. They probably are of Santa Fe age. At the contact with the basalt in two or three places the sandstone is "burned" to a bright red, fading in a few feet to yellow, then passing to the normal brownish color of the formation. At one place the tufa also is burned by underlying basalt, showing that the latter is intrusive, for if the basalt were older than the tufa, then the latter would have been deposited on the cooled, instead of on the intensely hot, surface of the basalt. Doctor Hewett reports the same phenomena at Black Mesa, north of San Ildefonso, and it is rumored that it occurs also near Buckman.

A description of the canyon of El Rito de los Frijoles in some of its principal features will answer for the neighboring canyons which cut the plateau and drain into the Rio Grande. A better understanding may be derived from the accompanying photographic illustrations. The canyon has been cut into the tufa by the stream, which through most of its course has not yet reached the base of the formation. Therefore the walls are composed wholly of tufa except for a mile or so above the mouth of the canyon, where, as indicated in the preceding paragraph, the stream has cut down into the basalt and sandstones. The important part of the canyon is 450 to 600 feet deep. The upper stretch consists of a deep, narrow gorge at the bottom of the canyon, scarcely 25 feet wide in places and 50 to 75 feet deep, widening out thence to the top by a terrace or series of terraces and slopes on each side, to a width of some hundreds of feet. This is all in the harder, upper tufa and beyond the limits of the portion of the canyon formerly occupied. Tributary gulches are also narrow and precipitous. Even here it is usually, though not always, much easier to ascend the southern wall than the northern one. Downstream, where the creek has cut deeply into the more yielding lower portion of the tufa, the bottom of the canyon widens into a valley several hundred feet wide at the bottom and 1,700 feet in width at the top, embracing a number of acres of tillable land, part of which

is now under cultivation and irrigated from the small stream. This wider portion of the canyon, less than two miles in length, was occupied by a considerable population in prehistoric times, and to some extent in more recent times, and contains the only agricultural land. This opening is the site of one large pueblo and several smaller houses, while cliff dwellings line the cliff on the northern side for a long distance. As this cliff recurs in all the canyons of the district, always on the northern side, and is of great archeologic consequence, it is more fully discussed in subsequent paragraphs. Still farther down, where the stream has cut into the basalt and sandstones, the canyon is again narrow. Strangely, instead of following the contact or cutting through the tufa, where the canyon reaches the hard basalt, it cuts through the basalt to great depth in order to reach the Rio Grande. In this vicinity the latter stream itself, instead of following the contact of the basalt and tufa or cutting the latter, has eroded a deep, narrow gorge though the basalt. The phenomena at the upper falls of the Rito de los Frijoles suggest that the basalt did not reach the top of the tufa when the canyon-cutting began or the stream would probably have cut into the tufa or along the contact; time did not permit, however, full investigation of this matter. If the gorge were well established when it reached sufficient depth to encounter the basalt, the stream would then have continued to cut downward along the same line instead of swerving from its course, according to the law which has been well named "the persistence of rivers." Just before reaching the Rio Grande the Rito de los Frijoles forms two cataracts of 60-foot and 90-foot fall, respectively, by plunging over two precipices of basalt in the bottom of the canyon.

This topography certainly existed virtually as at present during the occupancy of the canyon by the ancient pueblo and cliff dwellers, affording them a secluded retreat in a region difficult of travel. It is wholly impracticable to travel across the plateau in such direction as to intersect the canyons. The trails mostly follow the mesas which separate the canyons, or pass around their heads. Travel in the Frijoles canyon above or below the open valley is possible but difficult even on foot, which of course was the only method of travel available to the ancient inhabitants. Access from the south to the open part of the canyon is possible almost anywhere, though the slope is steep. On the north the vertical or nearly vertical cliff prevents access except in a very few places, making this side easy to defend.

The whole aspect of the region is that of immature topography. The land forms are abrupt. Steep cliffs abound. Angles have not even begun to give way to rounded outlines. The cutting of canyons has proceeded rapidly, from the geologic point of view, though that

A. LOWER EL RITO DE LOS FRIJOLES CANYON WHERE IT IS CUT INTO THE BASALT AT THE UPPER FALLS, THE SANDSTONE BELOW THE FALLS SHOWING NEAR ITS CONTACT WITH THE BASALT

B. WEATHERED SURFACE OF TUFA AT EL RITO DE LOS FRIJOLES

means very slowly from the standpoint of human history. At the old pueblo in the open part of the Frijoles canyon down-cutting has been almost at a standstill since the pueblo was built, possibly a thousand years or more. The grade of the stream here is gentle and the small volume of water has probably been so overloaded with débris swept in from the walls of the canyon as to be able to do no more than care for the load. A corner of the pueblo has been at some time destroyed. This may have been done by a flood, by undercutting in the ordinary meandering of the stream, which has swung across the valley more than once, or by recent Mexican inhabitants in the construction of a ditch along the edge of the terrace. Half a mile or more above the pueblo, stream terraces and trees furnish definite evidence on this subject, their positions on the banks of the creek showing clearly that at most the channel could not have been deepened more than five or six feet (probably less) since the sprouting of the rock pines, which are now 30 inches in diameter and probably at least 300 or 400 years old. At that rate the stream would have taken 30,000 to 50,000 years to cut the canyon. It is quite likely, however, that cutting has been somewhat more rapid during part of the past, as it seems almost certain that the volume of water was larger during the time of the great lakes and glaciers of the Southwest and the West. This is more fully discussed in the accompanying report on climatology.

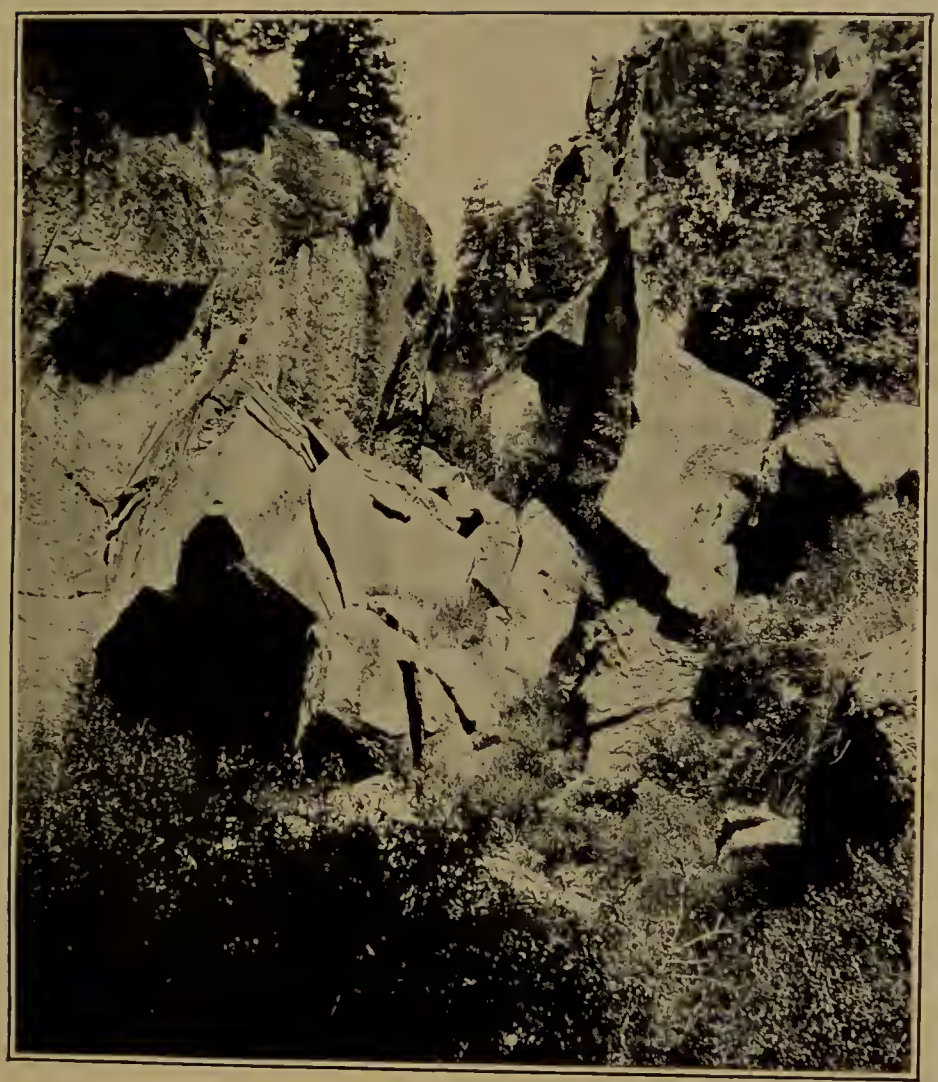
Wind, frost, and the beating of rains have also taken a prominent part in shaping the canyon. Without these forces the stream would have cut a much narrower canyon and would have performed the task in much less time. As soon as the stream made an incision in the tufa, rains began to beat upon the banks of the gully, crumbling the tufa, much of which is so friable that it may be picked to pieces with the fingers. After one terrific shower the writer found a quarter of an inch of débris from the cliff in a basin so placed as to catch the water draining from a small projection. This process has slowly widened the canyon and the resulting débris has hampered the stream in its downward cutting by forcing it to take care of much more material than that which it tore from the bed of the creek. Storm-water, getting into the crevices and interstices of the tufa, has doubtless frozen and in its expansion has pried off fragments of the material. Winds also have operated not only by carrying away the dust and small particles of tufa loosened by frost and rain but even by plucking small fragments out of the walls of the canyon. It is not unusual to see the wind blowing clouds of dust from the cliffs, and during a brisk wind one may hear pebbles dropping constantly along the canyon walls. Much of the fine material which fills the ancient ruins is windblown dust. The small cavities which honeycomb the cliffs have been formed by the wind, which easily excavates the yielding

material after breaking through the harder crust, so that the interior diameters of most of the cavities are greater than the diameters of the entrances. The great ceremonial cave at the upper end of the valley has been excavated chiefly by the wind in the softer material between two of the hard zones before referred to.

Whatever may be said of the past, all these forces of erosion are evidently working quite slowly at the present time. The plastering about the entrances to some of the caves remains intact, though the walls of the buildings which once stood before them have crumbled badly. Whether or not erosion is as rapid as formerly, at any rate the canyon has been cut by means of processes still at work in the region, and if there is a difference in the rate of erosion, no reason exists for considering the difference very great.

The same forces of erosion have an indirect influence on the vegetation, (1) by the production of dry mesas, better-watered canyons, and slopes varying in steepness and direction; and (2) by the production of exposures varying from indurated rock to fine soil. The chief exposure of indurated rock is the tufa, and, to a less extent, basalt, with still less of the sedimentary formation. The quartz crystals contained in the tufa form a large constituent of the soil, which is consequently very sandy. The disintegrated tufa forms the dominant soil of the region. On stream terraces, flood plains, and mesa tops the soil is rather fine. On canyon sides and talus slopes there is a larger admixture of angular fragments and of pebbles of tufa of widely varying size. The accumulations of humus soil are small; these occur here and there along the stream but are so insignificant as to deserve but little consideration. It is quite probable that occasional floods, which affect the banks of the streams where humus would otherwise accumulate, have prevented the formation of such soil, and away from the banks of the streams the aridity of the region would act as a preventive. At higher altitudes, where the humidity is greater and vegetation more abundant, there are larger accumulations of humus along the streams and on the forest floor. It is in such situations that fungus forms are much more abundant.

In the ruins are found selenite flakes, turquoise, pottery, and implements made of tufa, basalt, obsidian, schist, quartz, quartzite, and other rocks. The tufa, basalt, and obsidian were obtainable in the vicinity. Large beds of obsidian are reported elsewhere in New Mexico. The source of the selenite and clay is not definitely known, but probably they were not obtained in the immediate vicinity. Turquoise is found at several places in New Mexico. Beds of bowlders, including schists, quartzites, and other materials, such as have been used in making various implements, are found along the Rio Grande not far distant, as at Buckman. Some of the pottery contains much mica in tiny flakes.



UPPER RITO DE LOS FRIJOLES CANYON, WHERE IT NARROWS ABOVE THE RUINS

The use of tufa in the construction of the walls of buildings is a natural outgrowth of environment. Adobe earth and other convenient building materials are absent from the canyons and mesas of this district, while tufa is abundant, light, easily handled, and readily worked.

Water was furnished to the ancient inhabitants by El Rito de los Frijoles, a small rivulet across which one may easily step at almost any point during ordinary stages. The stream has its source in the Jemez mountains. Its volume responds very readily to meteorological conditions there. Twice during the summer of 1910, after a few days without rain in the mountains, the water almost ceased to flow for a few hours, and throughout August long stretches of the channel below the open valley were dry, only a tiny rill flowing over the falls. So far as present knowledge goes, desiccation would not account for the total abandonment of this valley, though it might account for a reduction of the population. It would support at present a small clan. The creek is so near the point of extinction, however, that it is altogether probable that during some of the dryer cycles it dries up entirely for a year or series of years. Indeed, the reported disappearance of trout, discussed in the zoologic report in preparation as Bulletin 56 of this series, strongly suggests such a drought within the last 20 years. The notable scarcity or absence of algæ, aquatic insect larvæ, and aquatic mollusks suggests the same thing. As no one has continuously resided there for any great length of time, definite information on this interesting phase of the subject is not yet obtainable. A few aquatic beetles were noted.

Returning now to the cliff on the north side of the canyon, whose archeologic importance has been mentioned, it is found to be the dominant feature of the landscape, which must at once impress every observer. At the base of the cliff are many artificial caves, connected to some extent with one another. They once formed rear rooms of dwellings, one to three or four stories in height, which were erected in front of them and the walls of which have long since fallen in. Everywhere much smaller cavities occur in the face of the cliff. If the artificial caves were not formed by enlarging some of the larger natural cavities, at least the idea of cave rooms was probably suggested by Nature's handiwork. The tufa composing the cliff can be easily excavated with the rude stone, bone, and wooden tools of the ancient workmen. Fortunately the cliff faces southward, so that the houses would be warm and dry in winter. The cave rooms also are perfectly dry, a condition which might not have obtained if they were on the south side of the canyon, where evaporation is less and some snow lies on the rocks for weeks at a time.

Below the caves and dwellings is a steep talus slope extending out into the valley. Above the top of the main cliff are several terraces

representing differential erosion of alternating hard and soft zones, rising one above another to the rim of the canyon. Along the base of the cliff, cones or "tent rocks" of tufa have been partially isolated from the canyon wall. Their origin is somewhat similar to that of "monument rocks" in certain parts of the West. Fragments of the harder upper tufa, sliding down steep slopes, came to rest, affording protecting caps for the soft tufa beneath them. Storms beating upon the portions of the slopes not thus protected wore away the material around the protected spots, leaving the latter standing out above and partially isolated from the slopes. The effects of this process, which is still in active operation, may be observed in all stages. Some of these cones are also developed by the dissection of the cliff immediately beneath a hard cap, a fragment of the cap rock being left in place by the weathering process. The south wall of the portion of the canyon where the ruins occur is notable for the absence of terraces, cliff, and cones, as just described, in place of which there is a fairly uniform slope of 35° to 45° from the horizontal. It is sparsely covered with piñon pines, cedars, shrubs, and other vegetation.

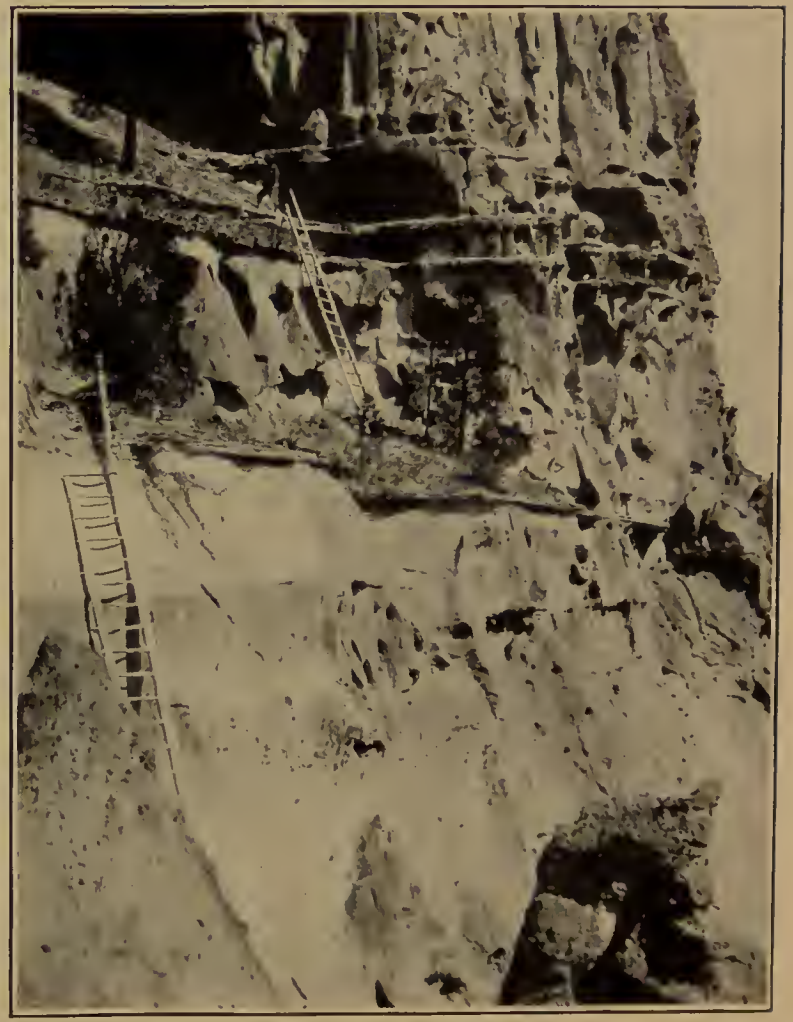
The recurrence of the steep cliff in all the canyons of the region, always on the north side, is an important feature of the environment of the ancient inhabitants. The origin of this peculiar topographic type is an interesting problem. Bandelier [1] attributed this condition to the beating of heavy rains from the south and east. He surely meant south and *west*, as storms from the south and east would pass directly up the Frijoles canyon, which he was discussing, and be as productive of results on one side as on the other. The prevailing direction of storms is not sufficient to explain the cliffs, but may be one factor. It is probable that several factors contribute to the final result.

A study of the recent meteorologic maps of the United States Weather Bureau [2] indicates that the prevailing winds are southwest. During the writer's visit to the region in August, 1910, the rainstorms came from west and southwest. Such storms, striking the north wall of the canyon at a high angle, would affect it more radically than the south wall, washing away much of the débris from the slopes and thus continually exposing fresh surfaces to subaërial erosion and at the same time preventing the accumulation of the soil necessary for the growth of a protecting blanket of vegetation. These storms would also actively erode the soft lower tufa more rapidly than the upper hard part, thus tending to form a cliff. The wind also would work in the same way. The opposite side of the

[1] Bandelier, A. F., The Delight Makers, p. 1, 1890.

[2] Linney, Charles E., Climate and Crop Service of the Weather Bureau, Annual Summary, New Mexico Section, 1905, 1906, 1907, 1908, and 1909, U. S. Dept. Agr.

A. TUFA CLIFF AT EL RITO DE LOS FRIJOLES, SHOWING "TENT ROCKS" AT THE BASE



B. TUFA CLIFF NEAR CEREMONIAL CAVE, EL RITO DE LOS FRIJOLES, SHOWING BANDING IN UPPER HALF OF THE FORMATION

canyon meantime would be more protected from such winds, while the rains would strike it at a very low angle and not be so effective.

Vegetation also is always an important factor in erosion on steep slopes. Very little force is required to move loose soil down a slope of 30° to 40°, but even scant vegetation helps to hold the soil and to permit its accumulation, its effectiveness being proportioned to the completeness with which it covers and sends its roots out into the soil. The quantity and character of the vegetation depends partly on the quantity of light, heat, and evaporation. The intensity of light and heat bear direct ratio to the angle at which the sun's rays strike the surface. Differential evaporation is governed largely by the angle at which both winds and the sun's rays strike the surface and by the velocity of the winds. Applying these laws to the area under consideration is a very complex task, the result of which must be unsatisfactory because of lack of knowledge of the relative values of the various local factors. El Rito de los Frijoles flows approximately southeast, while the canyon north of it runs more nearly east. Hence in the latter the sun shines on the northern wall practically all day, while at the Frijoles it shines all through the summer on the southern side of the canyon for some time in the morning before reaching the northern wall. However, the northern side receives the hottest rays during the middle of the day, and in the winter, when the sun is well south, it receives the rays at more nearly a right angle. The fact that clouds more often obscure the sun during the heat of the day than in the early morning is a factor on which it is difficult to place definite value. The direction of the prevailing winds is distinctly favorable to more rapid evaporation on the northern wall. Taking everything into consideration, the evaporation in all these canyons must be considerably greater on the northern than on the southern side. Innumerable observations in the southern Rockies and thence southwestward demonstrate that in arid and semiarid regions, where moisture is barely sufficient to support vegetation under favorable circumstances, a slight change in the direction of slopes is often vital. While the difference in this respect in the Frijoles canyon is not so radical as in many places, there is an observable difference between the opposite walls in the abundance of the smaller plants, which act as soil binders. In the course of centuries even a slight difference in the vegetal covering on steep exposures where conditions are otherwise near the critical point may make a marked difference in erosion. It is hardly believable that a factor so nearly universal in operation elsewhere should be wholly inoperative here.

Another possibility naturally suggests itself. If, after the canyon had reached two-thirds of its present depth, the whole region had been slightly tilted to the northward, the change would have thrown

the streams in that direction, causing them to undercut the canyon walls and thus produce cliffs on the northern side. Locally in the Frijoles and some of the other canyons such undercutting is going on now for very short distances. However, no evidence of such tilting has been discovered here.

With a hard zone above, and a thick, very soft bed of tufa below, such as exists in this region, any or all of the forces suggested would operate, perhaps, as causes in the production of more pronounced cliffs on one side than on the other, but all of them combined would not fully explain the present condition. With the same hard zone underlaid by soft material on the southern side of each canyon, surely high cliffs must form on that side unless some force not operative on the northern side is engaged in breaking down all incipient cliffs and terraces. That force is frost, one of the most effective causes of disintegration in all regions where water finds its way into crevices of the rocks and there freezes. Water in freezing expands about one-eleventh of its bulk or one thirty-fifth of its linear extent, exerting a force of a great many tons to the square foot. As snow occurs and water freezes in the region under discussion, it seems easy to account for the absence of the cliff on the southern side—the side facing northward. The tufa is deeply fissured wherever exposed, on both sides. Whenever the weathering of the soft material leaves one of the hard zones standing out on the southern side as an incipient cliff or terrace, water from winter storms finds its way into the crevices and freezes, thus prying off blocks of tufa and destroying all cliffs and terraces in their youth, leaving a fairly uniform slope. It is not difficult to understand why this does not also occur on the northern side. The northern wall, facing the south or southwest, receives the rays of the winter's sun at their most potent angle, and the cold is not so intense but that the rocks are thus kept well warmed, while the opposite wall of the canyon receives comparatively little heat during the coldest weather. Hence snow falling on the northern wall is soon melted and the water evaporates or runs off without freezing. Even in the most severe weather in northern Colorado, up to an altitude of 12,000 to 13,000 feet, where the snowfall is heavy, most of the southerly slopes are kept bare of snow through a great part of the winter. Much more would this be true at the Frijoles. Having reached this conclusion, the writer questioned Indians and whites who are familiar with the region, and they agreed that snow seldom remains on the northern side more than a few hours, but often remains on the southern side for weeks at a time. As differential erosion in a formation such as this would produce cliffs in the absence of any force tending to tear them down, the presence of a force which would tear down the cliffs on one side and not operate on the other

TUFA SHOWING HARD BANDS AND THE BEGINNING OF THE FORMATION OF "TENT ROCKS" OWING TO THE PROTECTION OF THE SOFT LOWER PART BY THE HARD BANDS

"TENT ROCKS," SHOWING TWO OF THEM STILL CAPPED BY THE PROTECTING FRAGMENTS OF HARDER TUFA

is both requisite and adequate to account for the existence of the cliff on one side and its absence on the other. That force is doubtless frost.

The importance of geologic and topographic phenomena and processes in the environment of both the ancient and the present inhabitants may be covered by the following summary:

The mountains influence temperature and precipitation, giving the region somewhat more rain than the arid region to the southwest receives. From the mountains flow several streams which afford water for the irrigation of tillable lands in their valleys. The Rio Grande, which is the principal stream, derives much of its water from the greater mountain ranges north of this region. The general slope of the country from the mountains to the river and the thorough dissection of these slopes by parallel canyons and their tributaries cause complete drainage and consequent absence of lakes, ponds, and swamps, which, if they existed, would harbor fish and waterfowl and add to the permanent water supply. This complete drainage makes the mesas very dry and the confinement of the streams to deep canyons makes the artificial irrigation of the mesas impracticable. The dry mesas seem unfavorable to the existence of game in large quantities, thus forcing the inhabitants to have recourse to agriculture. The topography vitally affects vegetation, certain trees and plants being confined to the valleys, others to the mesas. The varying altitude of the general slope from the mountains to the river marks off the region into somewhat definite plant-life zones, each with its characteristic species. The canyons afford many village sites easily defended from enemies. Villages built at the bases of vertical cliffs could be held indefinitely against a direct hand-to-hand assault, the chief danger being from the rolling of rocks from the tops of the cliffs. The easily excavated material of the cliffs made possible the many cave dwellings; even some of the ceremonial chambers and estufas occupy artificial or natural caves. The tufa furnished easily worked building material for the walls of the cliff dwellings, pueblos, and small houses. The weathering of the tufa furnishes the soil which is necessary for the existence of vegetation, and because of its origin the soil is very sandy. As the weathering is continuous, it constantly replenishes the soil, which is slowly carried away by storms. Such an environment would be apt to develop or to attract a rather sedentary people, agriculturally inclined, seeking seclusion from wandering warlike tribes and not dependent on the chase for sustenance.

CLIMATE AND EVIDENCE OF CLIMATIC CHANGES

BY

JUNIUS HENDERSON AND WILFRED WILLIAM ROBBINS

41

CLIMATE AND EVIDENCE OF CLIMATIC CHANGES

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Introduction

THE important bearing of climate on the culture of any region is evident. In the course of the investigation which has led to this paper there has been discovered no adequate, connected discussion of the subject, accompanied by an attempt to correlate the various lines of evidence of climatic changes for the region under consideration to ascertain whether they point in the same direction. It is found also that, though there is some direct and more inferential evidence of recent change of climate, it is meager, and there seem great possibilities of important discoveries by systematic investigation along several lines that have been pursued to only a slight extent. Therefore this discussion has been made more extensive than the subject at first might seem to warrant, in order to bring together the evidence, arguments, and literature, so far as they have come to the writers' attention, which may suggest lines of future work and aid field parties in the search for facts tending toward the solution of the problem. One of the greatest questions that has impressed those who have engaged in archeologic work in the Southwest is that of climate and climatic changes in relation to their influence on the cultures and population of the region. This problem is of a nature which does not permit of adequate discussion or investigation with reference to a small area, but involves the whole Southwest, and, in a sense, is world-wide. In the brief time at the disposal of the writers it is not hoped that the present treatment is final or exhaustive, or even that all the most important literature on the subject has been found.

It is not the purpose of this paper to attempt to prove that a progressive climatic change has occurred during the last several thousand years. The idea is rather to set forth and discuss fairly and frankly the evidence found which may bear on the question and to suggest lines of research that may throw further light thereon

Present Climate

No climatologic records are available for the immediate vicinity in which the writers' own work was chiefly done—El Rito de los Frijoles. The nearest United States Weather Service stations are at Española and Santa Fe, the former up the Rio Grande valley, about 18 miles

distant, the latter across the valley and somewhat more than 20 miles distant. The mean annual precipitation at Santa Fe is 14.8 inches, and at Española 10.5 inches. It seems probable that at the Rito de los Frijoles the precipitation is approximately 14 inches, a supposition finding support in the fact that the dominant plant formation (piñon pine and cedar) on the lower part of the mesas is the same as at Santa Fe. A short distance back from the rim of the Rio Grande canyon on the mesas and in the gulches rock pine is found, its presence indicating slightly greater precipitation.

The aridity of the region is clearly reflected by the vegetation. Such forms as the chandelier cactus (*Opuntia arborescens*), Rocky Mountain sage (*Artemesia tridentata*), rabbit brush (*Chrysothamnus* sp.), yucca (*Yucca baccata*), evergreen oak (*Quercus undulata*), and a predominance of composites tell one at a glance that the region is arid.

Figure 1 gives, for the purpose of comparison, the mean precipitation by months at Santa Fe, Española, New York, and St. Louis. The much greater precipitation at New York and St. Louis is at once apparent. The New Mexico stations have the greatest monthly amounts during July and August; the winters are dry. The annual march of temperature at St. Louis, Santa Fe, and Española are given in figure 2. The curves are similar, showing about the same distribution of temperature throughout the year. In northern New Mexico extremes of temperature, both diurnal and annual, are great. In the area dealt with in this paper the prevailing direction of the wind is southwest.

Evidence of Change of Climate in Other Regions

A recent change of climate in the Southwest having been frequently suggested, some discussion of the general question seems appropriate as bearing on the likelihood or unlikelihood of such changes here.

Huntington,[1] who has made extensive investigations in the Old World, gives much valuable information concerning the climate of the historic past, and is of the opinion that there have been such changes. His data relate to such phenomena as changes in the levels of lakes, length of rivers, distribution of plants and animals, ruins and other evidence of man's former occupancy of regions now deserted on account of unfavorable climatic conditions, and various traditions and legends. The waters of the salt lake of Pangong, on the side of the Himalaya mountains, seem to have receded within the period of human history. In the Lop basin of Chinese Turkestan the amount of vegetation has decreased within historic times and still shows signs of progressive desiccation, due not to human agency but to climatic

[1] Huntington, Ellsworth, A Geologic and Physiographic Reconnaissance in Central Turkestan, *Pub. No. 26, Carnegie Inst. of Wash.*, 157–216, 1905; The Vale of Kasmir, in *Bull. Amer. Geog. Soc.*, XXXVIII, 657–82, 1906; The Pulse of Asia, New York, 1907.

changes. The Basin of Turfan, the irrigation canals of Son Kul, and the Basin of Seyistan in Persia, and the Turkish lake of Gyul-Jük, together with much other evidence, all show, according to Huntington,

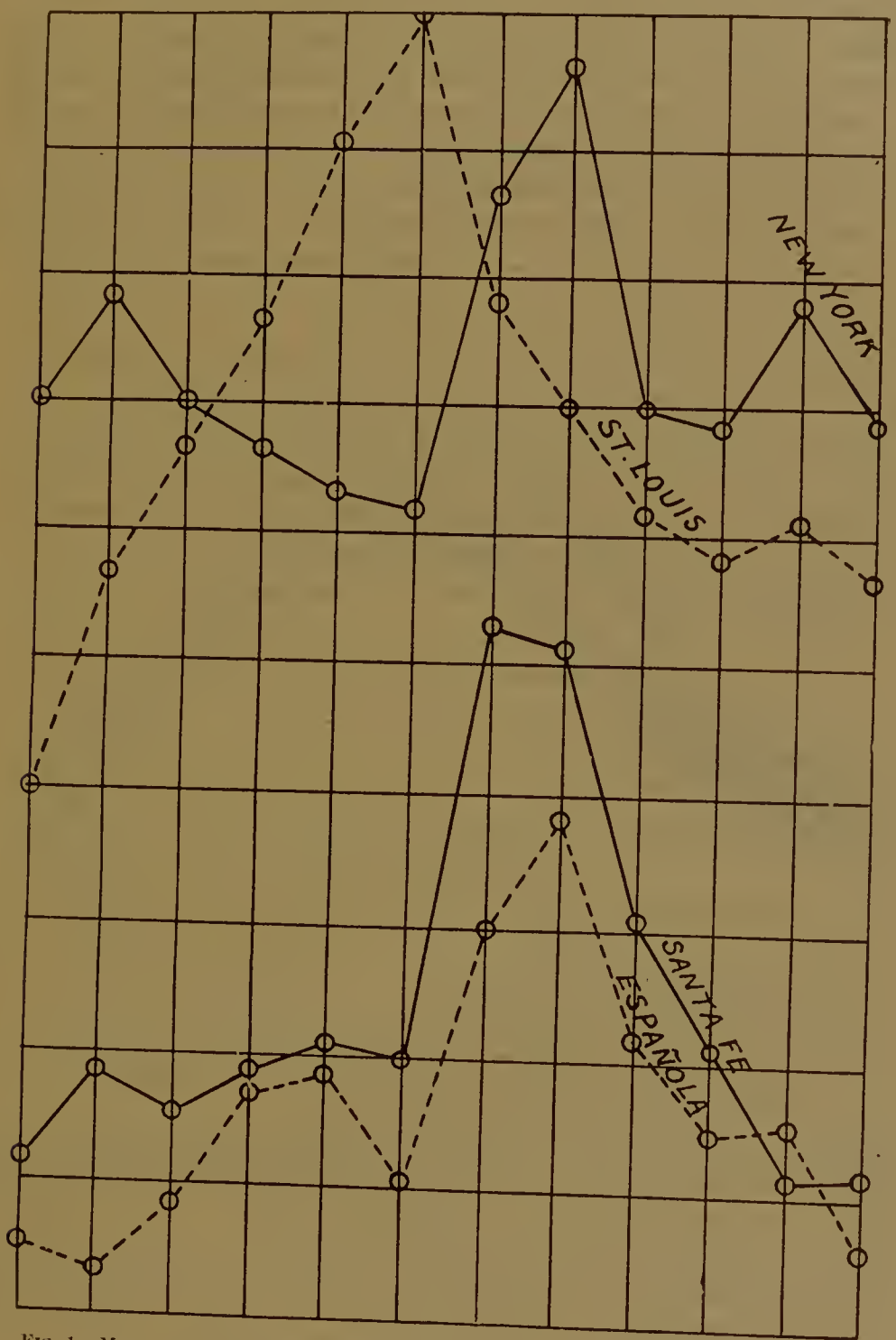

FIG. 1.—Mean precipitation, by months, at Santa Fe, Española, New York, and St. Louis.

the gradual drying up of the country. In the New World, he considers the migration of the Zuñi, the changes for the worse in agricultural conditions on the terraces of Peru, the extensive ruins of

Argentina and Bolivia, and other instances as evidence of climatic changes. Many travelers and explorers have brought forth evidence from other regions that climatic changes have been in progress during the last few thousand years.

Ward [1] tells of recent desiccation of lakes in Africa, one lake mapped as 30 miles long and 15 miles wide having been reduced to a few small ponds since 1859. Pope[2] shows that Devil's Lake, in North Dakota, has been materially reduced in area since 1883. Similar reports come from other quarters. It is well to note, however, that some travelers report encroachment of cultivated areas on

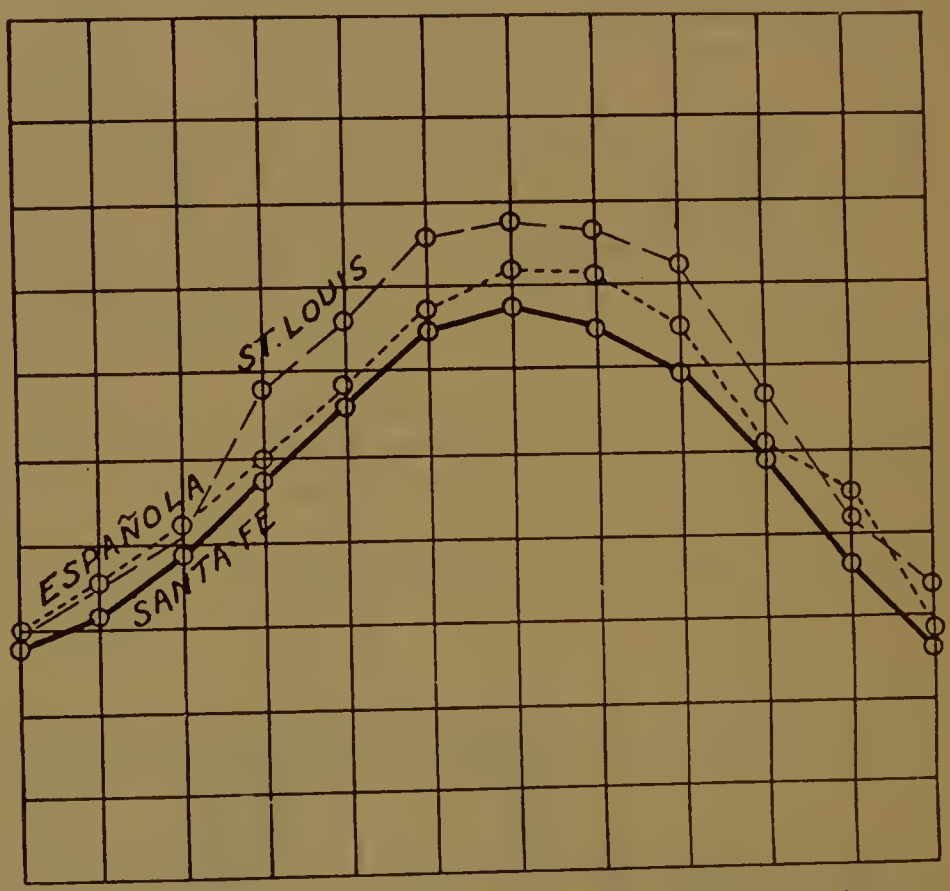

FIG. 2.—Annual march of temperature at St. Louis, Santa Fe, and Española.

deserts, a condition which may indicate that in places at least desiccation is not going on and which even suggests that possibly a very different interpretation may be placed on some of the evidence adduced in support of the desiccation hypothesis.[3] The area of lakes may be reduced by various causes other than change of climate, as, for example, silting up, vegetal growths in case of shallow lakes,

[1] Ward, R. De C., A Disappearing Lake, In *Science*, n. s., XXV, 114–15, 1907; Changes of Climate in Central Africa, ibid., XIX, 740, 1904.

[2] Pope, Thomas E. B., Devil's Lake, North Dakota, *Doc. No. 634*, U. S. Bur. Fisheries, p. 4 and map, 1908.

[3] Ward, R. De C., Current Notes on Meteorology and Climatology, in *Science*, n. s., XXV, 794–95, 1907; Changes of Climate in Central Africa, ibid., XXII, 251, 1905.

drainage by cutting down of outlet, withdrawal of water from tributary streams for irrigation, and prevention of run-off from adjacent territory into the lakes by the cultivation of the soil; or the change in area may represent merely temporary fluctuation in climate, as is known to occur with more or less regularity in cycles of a few years, so that in any given case it is well to refrain from hasty conclusions without sufficient acquaintance with all the facts. However, after all proper deductions are made, there still remains much evidence of recent changes of climate in various parts of the world. This subject is pursued somewhat further in the section on Geological Evidence of Change of Climate.

Archeological and Historical Evidence of Change of Climate

It has often been suggested by archeologists and others that the great number of ruins scattered throughout the Southwest in regions now deserted, apparently because of insufficient moisture to support a large population, points to the probability that within comparatively recent times the whole region has experienced great desiccation. It was a matter of almost universal comment among early as well as more recent explorers in the Southwest that the population was formerly much greater than now, and numerous traditions concerning the decrease in rainfall are reported. Loew [1] says:

> All the Spanish records, though sometimes very untrustworthy, agree in one point—the large number of inhabited towns. If the statements of the Spanish writers are founded on truth, the number of these towns was ten times that of the present pueblos, or Indian towns, while, by a close examination, we arrive at a number about four times as great. Some Spanish writers estimated the whole pueblo population at about 50,000; others, however, that of a single province at 25,000. As a proof of Spanish exaggeration, however, I may mention Castañeda's description of Acoma, a town which, according to his estimate, was inhabited by 5,000 persons, and was built in three parallel rows of houses. Now, I have visited this town and found the three rows of houses still existing. . . . But these rows of houses, which could never have been any longer, could not have held more than about 1,000 people. At present the population of the town is 800. Still it is an undeniable fact that New Mexico had a much greater Indian population formerly than now—a fact clear to anyone on viewing the numerous ruins. . . . Upon asking my Indian guide whether the former inhabitants of this town [near Jemez] were obliged to descend the steep and dangerous pathway every day to the creek to procure water, he replied that there were cisterns on the mesa, in which rain, formerly plentiful, was caught.

General vague Indian and Mexican traditions concerning the former abundance of water are of little value; these may have been suggested by the same physical phenomena as suggest the idea to modern white travelers. Definite traditions of the former existence and drying up of particular springs and streams, on the other hand, may have some value.

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[1] Loew, Oscar, Report on the Ruins of New Mexico, in *Ann. Rep. U. S. Geog. Expl. & Surv. W. of 100th Meridian for 1875*, pp. 174–78, 1875; *Final Report* of same Survey, vol. VII, 337–45, 1879.

Concerning Arizona, Ward [1] says:

There is evidence throughout that entire region that the amount of precipitation was formerly much greater than at present, and in so speaking I do not refer to a very remote date geologically, but to a period which was probably post-Tertiary. Indeed, from the present condition of many of the regions in which we know that the early Indians dwelt and which are now perfectly dry, with all sources of water so remote that they can no longer be inhabited, it must be inferred that there has been a change of climate within the period of human occupancy.

Speaking of the Jemez plateau, Hewett [2] says:

It appears that the abandonment of the cliff and pueblo villages of the plateau occurred from six hundred to eight hundred years ago as a result of climatic modifications by reason of which the hardships of living at these sites became unendurable. The transition from plateau to valley life was not necessarily sudden. There is no evidence of any great simultaneous movement from all parts of the plateau. The change was probably accomplished within a generation or two, one village after another removing to the valley or to more distant places, as the desiccation of the plateau proceeded. There is at present not a single stream on the east side of the Jemez plateau between the Chama and the Jemez that carries its water to the Rio Grande throughout the year. The ancient Tewa people were, as are their modern successors, agriculturists; hence, their living was dependent on the water supply. Only the most primitive style of irrigation was practiced and there is every evidence that the region was never rich in game or natural food products of any kind.

Of this region Loew [3] says:

Another fact observed here is worthy of mention on account of its bearing on the dryness of these regions, viz., the existence of deserted ant-hills here and there upon the isolated sandstone mesas of small extent. Here the ants construct their hills from much larger pebbles than do those in the Eastern States, the sweeping winds of this section easily blowing the small particles away and rendering firm structures necessary. Neither living nor dead ants were to be found, but legs and wings of insects that had served the ants for food were seen. Had the ants died in these hills, surely some of their horny tissues would have been left, as of the beetles. There is no doubt in my own mind that the ants had gone to the deeper valleys and cañons where some grass and consequently insects existed; the grass having died out on these mesas, bugs and beetles had taken their departure. This would seem to indicate increasing dryness of the climate of New Mexico, the inhabitants of which are convinced that it becomes drier and drier every year. "*El tiempo se pone mas seco cada año*," (the weather grows drier every year,) sighs the Mexican. They tell of springs and creeks that existed one hundred and some fifty years ago; indeed, even of some that have disappeared within the last fifteen years. Among these, a Mexican of Abiquiu mentioned the Rito Coyote, Rito Vallecito, and Rito Colorado de Abiquiu, all once existing in the mountains near Abiquiu. The provinces of Tiguex and Quivira, (the former on the Rio Puerco [*sic*], the latter east of the Manzana Mountains,) described by the early Spanish visitors as fertile countries, are now barren. Ruins of former Indian towns are found twelve to eighteen miles away from any water, one discovered by Lieutenant Whipple being fifteen miles north of the Rio Mancos. There must certainly have been water in this section formerly. [p. 133.]

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[1] Ward, Lester F., Status of the Mesozoic Floras of the United States, in *Monogr. U. S. Geol. Surv.*, XLVIII, pt. I, p. 23, 1905.

[2] Hewett, Edgar L., Antiquities of the Jemez Plateau, New Mexico, *Bull. 32, Bur. Amer. Ethn.*, p. 13, 1906.

[3] Loew, Oscar, Report upon the Agricultural Resources of Northern New Mexico and Southern Colorado, with Analyses of Soils, Plants, etc., in *Ann. Rep. U. S. Geog. Expl. and Surv. W. of 100th Meridian for 1875*, pp. 133, 135-36, 1875.

About five miles below Santa Fé, directly on the arroyo del Santa Fé Creek, is the Mexican town Agua Fria, (cold water,) rather a misnomer at present, since the water has to be brought in barrows a distance of two miles, there being none in the vicinity of the settlement. On inquiry, I was informed that about one hundred and fifty years ago the Santa Fé Creek was full of water, and that its margins were fringed with willows and alamos, whose shade kept the water cool; but the water sank gradually into the sand and the trees disappeared. . . . In my own opinion the sinking of this stream is due not only to the gravelly character of the river-bed, but also, and much more, to the diminished water-supply from the mountains—a fact attributable partly to the disappearance of extensive forests once upon them, and partly to a diminished precipitation upon the mountain and lowering of the level of the whole region as above explained [pp. 135–36].

The disappearance of the ants may be due to some cause other than drought, and even if due to drought would indicate perhaps a dry year or cycle rather than progressive desiccation. So, the sinking of the water in Santa Fe creek, if correctly reported, may be due to causes other than diminution of flow. However, these statements are suggestive for future observation and investigation in the region.

Cummings [1] says of the San Juan Valley:

The evidences of a more extensive growth of oak and pine, the presence of cisterns and reservoirs where now it would be impossible to obtain enough surface water to fill them, and the location of large villages where now it is impossible to develop in the springs formerly used for the water supply enough water to satisfy the needs of a small camp, all tend to show that there has been a gradual lessening of the rainfall and a consequent drying up of many of the springs. Land formerly capable of producing a good crop under primitive methods of cultivation, ceased to respond to the efforts of the planting stick and horn spade; and man was forced to search for a new location. Long periods of drought, with consequent famine and disease, probably played their part also in weakening and diminishing these people; until the remnants became an easy prey to the piratical Ute and the warlike division of the Navajos. Thus, gradually absorbed and forced southward, one group after another lost its tribal identity, and lives today only in the vague traditions and myths of the Zuni, the Hopi, and the Navajo.

Writing of southwestern Colorado, Holmes [2] says:

At first, it seems strange that a country so dry and apparently barren as this now is could support even a moderate population, and it is consequently argued that the climate has grown less moist since the ancient occupation. Be this as it may, I observe the fact that the great bulk of remains are on or in the immediate neighborhood of running streams, or by springs that furnish a plentiful supply of water during the greater part of the year. The ever present pottery may in many cases have been broken and left by hunting and wandering parties, and the remnants of dwellings far out from water may have been but temporary abodes used only in the winter or during rainy seasons. I also notice that the country is by no means an entire desert. All along the stream-courses there are grass-covered meadows and broad belts of alluvial bottom, affording, if properly utilized, a considerable area of rich tillable land.

[1] Cummings, Byron, The Ancient Inhabitants of the San Juan Valley, *Bull. Univ. Utah*, vol. III, no. 3, pt. 2, p. 45.

[2] Holmes, William H., Report on the Ancient Ruins of Southwestern Colorado, Examined During the Summers of 1875 and 1876, in *10th Ann. Rep. U. S. Geol. & Geogr. Surv. Terr.* (Hayden Survey), for 1876, p. 383, 1878.

Hoffman,[1] writing of northwestern New Mexico, says:

That the country was agriculturally good, well watered, and wooded, we have proof from a mere glimpse. Since the climatic change it is not fit to support life in the great majority of cases.

He attributes the alleged change of climate to the cutting away of forests by the ancient inhabitants; for this conclusion he offers no proof, and with his argument all men do not agree.

Speaking of the region about one hundred miles south of Santa Fe, Morrison[2] says:

North of the Oscuras are the Chupadero Mesas, a low table-land cut up by almost innumerable cañons and drains, well grassed, but perfectly dry, excepting the little water at Chupadero Spring, which has been developed and a tank dug to hold the limited supply. Here we found one of the old Spanish ruins. The foundations of the houses and the churches still remained. Here, where we now find but water sufficient for one family, formerly lived several hundred people, in stone houses—the early Spaniards and their Indian slaves [*sic*]. In the dry mesas to the east are still other ruins. About 15 miles to the east is the Gran Quivira ruin, the largest of these Spanish relics. Fifteen miles from water of the present day lived in this town probably several thousand people. . . . Walled-up cisterns, apparently for the public use, were found at the crossings of streets. . . . Several square miles of ground about the old town had been under cultivation, as was apparent from the vegetation. . . . In all this country there is not now a drop of permanent water, such changes have three hundred years made. The country described by Juan Jaramillo, one of Coronado's captains, in 1542, as being "as beautiful as any he had seen in all France, Spain, or Italy, and watered by many streams," is to-day utterly dry, covered, to be sure, with nutritious grasses, but otherwise almost a desert.

Of northwestern New Mexico, Cope[3] wrote:

Perhaps the most remarkable fact in connection with these ruins is the remoteness of a large proportion of them from water. They occur everywhere in the bad lands to a distance of twenty-five miles from any terrestrial source of supply. The climatic character of the country there has either undergone material change, or the mode of securing and preserving a supply of water employed by these people differed from any known to us at the present time. I found no traces of cisterns, and the only water holders observed were the earthenware pots buried in the ground, which did not exceed eighteen inches in diameter. There is, however, no doubt that these people manufactured great numbers of these narrow-necked globular vessels, whose principal use must have been the holding of fluids, and chiefly of water. Nevertheless, it is scarcely conceivable that the inhabitants of the houses now so remote from water could have subsisted under the present conditions.

On the other hand Hough,[4] in discussing the Gila valley, farther southwestward, says:

There was probably not one village surviving in this vast area at the time of Coronado's journey; but the ancient ruins, by their profusion, indicate that a compara-

[1] Hoffman, W. J., Report on the Chaco Cranium, ibid., p. 455–56, 1878.

[2] Morrison, Charles C., Executive and Descriptive Report of Lieutenant Charles C. Morrison, Sixth Cavalry, on the Operations of Party No. 2, Colorado Section, Field Season of 1877, in *Ann. Rep. U. S. Geogr. Expl. & Surv. W. of 100th Meridian for 1878*, pp. 136–37, 1878.

[3] Cope, E. D., On the Remains of Population Observed On and Near the Eocene Plateau of Northwestern New Mexico, in *Ann. Rep. U. S. Geogr. Expl. and Surv. W. of 100th Meridian for 1875*, p. 172, 1875; *Final Report* of same Survey, vol. VII, pp. 351–61, 1879.

[4] Hough, Walter, Antiquities of the Upper Gila and Salt River Valleys in Arizona and New Mexico, *Bul. 35, Bur. Amer. Ethn.*, pp. 10–11, 1907.

tively dense population once lived there. What, then, were the causes which led to the extinction of these people? So far as may be inferred from present conditions, the environment was favorable for the maintenance of Indian tribes, and it is probable, therefore, that there is no geographic or climatic condition adequate to explain the depopulation of the whole region. In some sections disease may have checked the growth of population and finally exterminated the inhabitants, for even in the elevated localities fevers of a certain class bear heavily at times upon the present settlers. In some of the river valleys malaria also at times is prevalent. On the whole, however, the climate is salubrious. Exploration of the ancient ruins, so far as this has been accomplished, invariably shows, moreover, that the abandonment of the pueblos was not due to internal warfare or to attacks by outside enemies. In reference to the failure of the food supply, due to prolonged drought or other circumstances, there is reason to believe that such failures were less prevalent in former times than in the years since the occupancy by white men. However, starvation may have been a factor in the decline of population in certain localities. It may be that the most potent cause existed in the social organization of the people, coupled with the isolation enforced by the environment. It is known that the social organization of the existing Pueblo tribes among which marriage is prohibited within the clan tends to self-extinction, and it is possible that the tribes of the Gila suffered from the same cause. . . . The evidence invariably shows that no sudden cataclysm overwhelmed the pueblos; no hasty, disorganized abandonment took place, no wars decimated them, but rather that, like a tree, they passed through successive stages of growth, decline, and decay to final extinction.

Fewkes[1] takes another view of the cause of abandonment. He says:

The prehistoric population of the Gila Valley may have risen into the thousands, and it is not too much to say that the number of Indians in the valley at the advent of the Spaniards could not have been more than a tithe of what it was in prehistoric times [p. 406].

It appears that the valley of the Salt River in the neighborhood of Phoenix, Tempe, and Mesa was the most densely populated region of this whole drainage area and apparently contained the oldest settlements. These facts may be ascribed to the ease with which the plains in this region could be irrigated as compared with other parts of the valley, or may have been due to the presence of more fertile land in those localities [p. 407].

The extent of the aboriginal ditches that can be traced for miles shows that the prehistoric inhabitants had discovered and applied a more extensive system of irrigation than any of their contemporaries who dwelt in other sections of what is now the United States. . . . It is probable that certain clans were driven away from their homes and forced into other regions by the changed conditions, as the inroads of hostiles. This theory is in fact supported by legends still told by the Hopi and other Pueblo people. . . . The author would state in conclusion that he believes the abandonment of the Casas Grandes was brought about by an invasion of nomads from farther down the river in prehistoric times [pp. 434-36].

Mindeleff[2] suggests that the many droughts and constant variations and local changes in water supply compelled frequent removals and rebuilding, so that the number of ruins by no means indicates the number of former inhabitants.

[1] Fewkes, J. Walter, Prehistoric Ruins of the Gila Valley, in *Smithson. Misc. Coll.*, LII, 406, 407, 432, 434, 436, 1909.

[2] Mindeleff, Victor, A Study of Pueblo Architecture in Tusayan and Cibola, in *8th Ann. Rep. Bur. Amer. Ethn., for 1886-87*, pp. 23, 227, 1891.

Bandelier [1] long ago pointed out the danger of hastily inferring a change of climate from the mere fact that extensive and numerous building sites are now abandoned, and suggested such possible causes of abandonment as war, pestilence, flood, earthquake, or other calamity, destroying the buildings, decimating the tribes, or frightening them away. He also declared that numerous ruins do not necessarily indicate a large ancient population, as some of the tribes still preserve traditions of several more or less local migrations and consequently of the occupancy of several village sites; that epidemics have occurred in historic times; that some of the villages were provided with artificial reservoirs for storing water; that there are more springs than is generally supposed, such watering places, "artfully closed by the Indians," being now occasionally discovered in the immediate vicinity of the ruins; that a mile from the river banks is not looked on as an inconvenient distance to carry water for household purposes; that springs have been known to be affected by earthquakes in the Southwest, a fact which might account for their absence now; that pueblos might be ten or fifteen miles from their fields, as at Acoma; and that "Indian corn, of the small variety, bushy, with long ears but a light grain, will grow without artificial watering wherever the rainy season is tolerably regular, as upon the mountain slopes."

He says further, in the same report:

> I do not in the least doubt the accuracy of the statement as to the large number of settlements spoken of. But it does not follow that they were all flourishing at the same time. I cannot sufficiently insist upon the many changes of abode customary among the most sedentary Indians in their primitive state. . . . The country lacks the elements of support for a large population. That the sedentary Indian changes his location and his plan of living easily, under the pressure of physical causes and of danger from enemies, outweighs any explanations based upon hypothetical climatological changes, or upon geological disturbances supposed to have taken place since the first appearance of man in the country [p. 301].
>
> It is a well known fact that the Indian is expert in closing springs. They have been discovered in places where for decades they have been sought in vain; and invariably they have been found to be filled and every trace of them on the surface obliterated in the most skillful manner [p. 305].

Speaking of a discovery by Chaves, Bandelier says, quoting Lummis:

> In crossing a barren plain west of his home at San Matéo, and near some undistinguishable ruins, he noticed that a bit of ground 'gave' under his horse's feet. Dismounting to investigate, he found that a small area seemed elastic and moved up and down when he jumped. Being of an inquiring turn of mind, he took men out to dig there. They removed about a foot of earth over a place some ten feet square, and came to a deep layer of long strips of cedar bark. Below this was a floor of pine

[1] Bandelier, A. F., Final Report of Investigations Among the Indians of the Southwestern United States, Carried on Mainly in the Years from 1880 to 1885, part II, *in Papers Archæol. Inst. Amer., Amer. ser.*, IV, 11–23, 75–77, 1892.

logs, then another thick layer of bark, and so on down for several feet. Below the last layer they found a little spring of clear, running water, which has resumed running since they dug it out after centuries of enforced idleness. So thorough had the ancient owners been in their work that they had even obliterated the long, shallow gallery through which the waters of the spring used to escape [pp. 307-08].

The force of these warnings is evident and yet not entirely satisfying when they are applied to the Rito de los Frijoles and the surrounding territory. The ancient ruins in the canyon itself once must have housed some hundreds of people even if all the ruins were not inhabited contemporaneously, and there is nothing to indicate that they were not practically all occupied at the same time. Bandelier, who is conservative, places the population at 1,500 (op. cit., p. 141). In addition, the ruins of old dwellings are to be found everywhere on the adjacent mesas and scattered throughout the other canyons which cut the plateau. The mesa dwellings are not so situated as to indicate that they were placed on elevated ground for protection from enemies, and it seems wholly improbable that their occupants would have lived in such places if they were dependent for food on crops in the canyons. It is also inconceivable that they would have lived on the mesas with their water supply in the bottoms of the canyons, 450 to 600 feet below them, unless the canyons were already occupied and their tillable land was taken up by others. No extensive irrigation works on the mesas have yet been discovered which would provide irrigation for crops, and carrying water for irrigation to the mesas from the nearest present sources would have been quite impracticable, yet there is no reason to believe that corn could now grow on the mesas in the vicinity of these ruins. The country is not and probably has not been rich in game. It is difficult to believe that so many people would have built on the mesas unless they could have raised crops there without irrigation. With fertile valleys, good water, and better opportunities in the bottoms of the canyons for protection and seclusion from enemies, it seems very much more likely that they would have occupied the valleys alone unless there were more inhabitants than the limited valley areas would support. Hence a logical conclusion is that probably most of the dwellings in the canyons and on the mesas were occupied simultaneously at some period. The fact that it was not necessary to live near the fields would hardly account for the placing of the homes on the high dry mesas, because locating them here would add to the distance and altitude to which the grain and water must be carried. It is also wholly improbable that any great number of springs was destroyed by earthquakes or concealed by the inhabitants on abandoning the dwellings, without many of them, or, indeed, most of them, revealing themselves now by seepage, while if destroyed by desiccation, that would put an end to them and stop seepage.

It is certain that these ancient dwellings were not ruined by floods. Most of them are so situated that no flood could affect them. The large pueblo in the bottom of the Frijoles canyon may have had one corner cut away by a flood many years ago, but this is not certain. The outline indicates that a small portion had been destroyed; but, in the writers' examination, two equally plausible explanations suggested themselves: (1) That instead of a flood, the ordinary meandering of the stream, which has repeatedly swung back and forth across the valley, as shown by the terraces, may have undermined that corner. (2) That an irrigating ditch, which was constructed probably after the original abandonment (for the canyon has been reoccupied during the last century by both Mexicans and Americans) may have destroyed that portion. At any rate, floods probably had nothing to do with depopulating the canyons or the mesas.

There seems no reason for supposing that these buildings were shaken down by earthquakes. The walls do not present the appearance of having been partially destroyed by earthquakes, and it seems unlikely that the vertical cliffs, thoroughly fissured, at the base of which were some of the buildings, could have withstood a severe earthquake without huge blocks having been tumbled down. An examination of both ruins and bluffs at El Rito de los Frijoles seems to preclude the earthquake theory. Furthermore, experience of other peoples in other regions has shown that even great disasters do not drive them away permanently. People have been known to swarm back to the slopes of volcanoes almost before the lavas of destructive eruptions have had time to cool.

Evidence of a general destruction or expulsion of the inhabitants by war has not yet been discovered. In case of sudden abandonment on account of an invasion or pestilence abundant evidence would have been left behind. This of course does not forbid the conclusion that the tribe may have been gradually weakened by war, pestilence, and starvation until only a remnant was left to migrate to a more favorable locality.

It is estimated that the ruins of the Frijoles canyon and the vicinity have been abandoned for at least 800 or 1,000 years, perhaps longer. They were in almost as poor a state of preservation as now when first discovered by white men, and under present climatic conditions, with very little frost affecting most of the cliff dwellings, the destruction of the walls must have consumed a long period. Furthermore, the abandonment itself was probably gradual, not sudden. Hence it may be safely said that at least 1,000 to 1,500 years must have elapsed since the most flourishing period of the occupancy of the region by its ancient inhabitants. It is difficult of course even to approximate the extent of that period of occupancy, but it must have been at least some centuries. If progressive desiccation were the

cause of the abandonment of the dwellings, then it is almost certain that the mesa dwellings were first abandoned, the people possibly crowding in the beginning down into the canyons, where conditions remained more favorable, and overpopulating them. As crops may still be raised in the limited bottom lands of the canyons, especially in the few (as Frijoles canyon) containing small streams available for irrigation, they would naturally be the last to lose their population.

If there has been progressive desiccation of the region it would be fully adequate to account for the abandonment of these ruins by the rather large population which probably once occupied them. Then, inasmuch as the same condition is found over a very large area, indicating that in the whole now arid region the aggregate population must have been very great, the question would arise, where did they go? It is not sufficient to say merely that they were driven out. A general migration to some distant region where conditions are more favorable would probably have left a well-defined trail in the traditions of the whole region. Numerous traditions of local migrations are known, but all should be scanned with care before acceptance.[1] It seems to the authors that a much more reasonable explanation of the known phenomena is this: If the rainfall slowly decreased, conditions must have become very gradually more severe. More and more frequent droughts and accompanying starvation periods would result, during which the weaker members of the tribe would perish, not altogether from starvation, but from the reduction of their powers of resistance to disease, cold, and other hardships through want of sufficient nourishment. Thus the general physique of the tribe would be preserved by the weeding out of the unfit instead of weakening the physique of the tribe as a whole. As the severity of such droughts increased it is probable that minor wars for the possession of the small, better-watered tracts would occur, still further reducing the various tribes and decreasing the aggregate population of the region. Occasional minor epidemics would be apt to reduce still further their numbers, especially if they occurred during periods of drought. Thus it is reasonable to suppose that as a natural result of desiccation the population decreased so gradually that the decline could be discovered only by very accurate statistical records or by a general comparison of the numbers living in the region at widely separated periods. In this way the depopulation would progress slowly by natural processes and therefore would not attract the attention of the inhabitants and would leave little impression in their legends or traditions. The remnant of the population would gradually move in small bands to situations favorable to agricultural pursuits, thus becoming widely dispersed.[2] The foregoing changes

[1] Hewett, Edgar L., The Excavations at El Rito de los Frijoles in 1909, *Papers School Amer. Archæol.*, no. 10, pp. 670, 672, 1909.

[2] Hewett, Edgar L., Antiquities of the Jemez Plateau, *Bull. 32, Bur. Amer. Ethn.*, pp. 12–13.

would be expected to occur in a region which was slowly drying up, and present conditions are just such as one would be led to expect. Hence it seems very probable from the archeologic evidence that there has been progressive desiccation.

Botanical Evidence of Change of Climate

It would naturally be expected further that a change of climate would leave some impression on the native vegetation by which it could be detected. Climatic changes are necessarily gradual, and much of the vegetation could slowly adapt itself to the progressive changes by change in characters and habits to enable it to meet the altered conditions; but if the change is still in progress or has very recently ended it would be apt to manifest itself in the relations of plant formations to one another and in "relicts" or stragglers left over in the most favorable habitats.

While it is true that during 3,000 years some species may be altered to a slight extent, others may be introduced by various means, and others may come into existence suddenly (mutation), and that the relations of formations and associations of plants may have changed in some measure, yet it is highly improbable that there has been a marked and widespread modification of the flora within that time. However, the relation of the two principal plant formations of the region seems to afford some evidence of progressive climatic change. This may be seen in the stress zone between the piñon pine-cedar formation and the rock-pine formation. Piñon pines and cedars grow in drier situations than do rock pines. In the area under discussion rock pine occurs on the higher parts of the mesas, back toward the mountains, while piñon pine and cedar are confined to the lower portions, down toward the rim of the Rio Grande canyon. At a distance of one to three miles back from the Rio Grande the two formations meet and here there is a battle for occupancy of space. If in this struggle between these two plant formations the piñon pine-cedar formation is the successful competitor and gradually encroaches on the rock-pine formation, and if such encroachment is widespread, this condition probably indicates progressive desiccation of the country. That is the condition in this region. If the rock-pine formation were extending into the territory of the formation below it, there would be rock-pine seedlings as outposts of the invasion, and their presence would be evidence that conditions in the new territory were favorable for their growth. From the lower extension of the formation rock-pine seedlings are almost entirely absent. The outermost individuals are large trees, in many cases the largest of the formation, possibly several centuries old, indicating that in the early stages of their growth conditions were more favorable for the species to obtain a start and that no such favorable period has occurred since.

Piñon pine and cedar seedlings do occur at the stress zone, although not in greater abundance than at any other point in the formation. The whole aspect of the line of stress between these two formations shows that the piñon pine-cedar formation is encroaching on the rock-pine formation, a condition which would not exist unless there is progressive desiccation which is tending to make the debatable territory unfavorable for the rock pines and better suited for piñon pines and cedars.

Along the Santa Fe railroad in Arizona observations were made which have some bearing on the subject. Between Winslow and Flagstaff the elevation gradually increases from 4,800 feet to 6,800 feet. At Angell the juniper belt is well developed, with a few piñon pines between. As the elevation increases, piñon pines become relatively more abundant, and occasionally large lone rock pines are seen. It is significant that the rock-pine outposts are large individuals, scattered here and there. In the neighborhood of these large trees no seedlings were noted; there were, however, numerous piñon pine and cedar seedlings. Many large dead rock pines occur: these do not seem to have been killed by fire or disease, and there are too many of them to ascribe their death to lightning. It is not at all improbable that drought is the cause of the fatality in this case. On the western slope of the divide, after leaving Flagstaff, no such relation as mentioned for the eastern slope exists. Here the outposts of the rock-pine formation are not especially large, nor is there an absence of seedlings at the edge of the formation.

A thorough study of the vegetal stress zones in the Southwest would undoubtedly shed much light on the question of climatic changes. It is impossible to assign much importance to fragmentary observations, as the foregoing necessarily are, until they are seen in connection with more extensive data, such as a general study of the Southwest would bring out.

Any changes which may have occurred during the last few centuries should be revealed by an extended study of the growth rings of coniferous trees.[1] Many such trees in New Mexico and Arizona are from 300 to 500 years old, and some doubtless even older.

Although slight changes have been and still are in progress in the vegetation, pointing to the gradual drying of the country, it is not necessary to suppose that these changes have been extended or radical. There is little reason to doubt that the ancient inhabitants who lived in the cliffs along the northern wall of the Frijoles canyon looked out on a stream fringed with cottonwoods, boxelders, birches, and alders, that they saw tall rock pines against the background of the canyon wall, and that the piñon pines and cedars were as familiar to

[1] Douglass, A. E., A Method of Approximating Rainfall Over Long Periods and Some Results of its Application, in *Science*, n. s., XXXVII, 33, 1913.

them as to those now living in the region, though the boundaries of the formations were probably at slightly lower elevations than now. These things were part of the cliff-dwellers' environment as they are part of the present environment.

Though it seems highly probable that the disappearance of the inhabitants from the region was due to progressive desiccation, it need not be assumed that climatic change has been very great, and surely it was not sudden. If the precipitation was once just sufficient to make corn-growing on the mesas profitable, a decrease of only two or three inches in the mean annual precipitation would make it impossible without irrigation and at the same time would make irrigation of the mesas impracticable. Such a decrease would cause also the disappearance of springs which may have provided water for the mesa-dwellers.

It is probable that the culture exhibited by the archeologic evidence of the region was developed under conditions almost if not quite as rigorous as those of the present time. That this was Powell's opinion is evident from the following quotation:[1]

> The Pueblo peoples, ancient and modern, grew up under hard environment; shadowed ever by the specters of thirst and famine, they were exceptionally impressed by the potencies of pitiless nature and the impotency of their own puny power; and like other desert peoples, seafarers, and risk-haunted folk generally, they developed an elaborate system of ceremonies and symbols designed to placate the mysterious powers. The ruins of the prehistoric settlements abound in relics of the ancient tribesmen and their mystical cult; and the relics are largely interpretable through researches in the modern pueblos. Occupying an arid region in which water is the most precious of all commodities, the Pueblo peoples early acquired skill in the manufacture of utensils adapted to the conservation of water, and eventually became the potters par excellence of aboriginal America.

The precipitation of the region has passed below the critical point for corn-growing without irrigation, and so far as the archeologic evidence shows, this was the chief crop of the ancient inhabitants, but the slight change of climate which would make corn-growing on a large scale impracticable might not produce much change in the general appearance of the uncultivated vegetation.

The phenomenon of succession in vegetation is universal. Geology points to the fact that one type of vegetation is gradually replaced by other types. These geologic successions are in many cases attributed to climatic changes. There are, however, successions of vegetation going on at the present time. But the changes which take place from century to century are for the greater part due to changes in soil, not climatic conditions. However, there seems to be some botanical evidence, although meager, indicating changes in vegetation, due to climatic variation, within the last several thousand years.

[1] Powell, J. W., *Seventeenth Rep. Bur. Amer. Ethn.*, p. lxxii, 1898.

Lewis [1] has investigated the plant remains in the peat bogs of England and Scotland. In the lowest strata are arctic willows, above these are forest remains, followed by the present-day peat mosses. In the Cross Fell chain, peat beds having forest remains cover about 140 square miles; the present forest extends over only 11 square miles. Lewis thinks that the destruction of these forests has been due to "climatic changes acting over very long periods of time." Studies of forest successions in Europe indicate that they, too, are due in some cases to climatic changes.

As already said, botanical evidence of changes of climate within historic times is meager and not convincing. It is a field of study to a large extent untouched, a study beset with difficulties. Methods of investigation are not worked out. Successions of vegetation have and are taking place, but the relative importance of climatic and other operating factors is difficult of analysis.

Any change of climate would be very slow.[2] The fact that meteorologic records fail to show such change is of little importance, for such records extend over only a few centuries and accurate records over only a very short period, during which the change, if in progress, would be too slight to manifest itself in averages, besides being masked by probably more or less periodic fluctuations, while the accumulated change of 2,000 or 3,000 years, if records were available, might be quite manifest.

It is improbable that change of temperature has had any direct bearing on the disappearance of the ancient dwellers from this region. Present temperatures are suitable for agriculture and for comfortable living. However, if there has been an increase in the mean annual temperature, as is not at all improbable, it would have increased the evaporation, thus making greater precipitation necessary for agriculture and in that way indirectly aiding in depopulating the area.

Speaking of the region west of Albuquerque, Newberry [3] says:

> In all this region a fact was observed, to which our attention was first called on the banks of the Little Colorado, viz: that the lower hills and the bases of the highlands are covered with dead cedar trees, an apparent indication of the increasing dryness of the climate. The timber in this country is confined to the more elevated surfaces, where the precipitation of moisture is greatest, and the belts of deadened trees, certainly untouched by fire, prove that the conditions favorable to the growth of arborescent vegetation are becoming restricted to narrower limits. This fact is mentioned merely as being confirmatory of the conclusion drawn from other data, that the amount of rain on the table-lands west of the Rio Grande is now much less than formerly.

Many dead cedars occur also on the mesas west of Santa Fe. Mistletoe is a pest there and may have caused their death, or it may, of

[1] Lewis, Francis J., Plant Associations in Moorland Districts, in *Nature*, LXXI, 257–58, 1905.

[2] See Sullivan, Richard H., The So-called Change of Climate in the Semiarid West, in *Yearbook U. S. Dept. Agric. for 1908*, pp. 289–300, 1909.

[3] Newberry, J. S., Geological Report, *Report upon the Colorado River of the West, Explored in 1857 and 1858 by Lieutenant Joseph C. Ives*, pt. III, p. 96, 1861.

course, be due to disease, insects, or other causes. Not having examined the region referred to by Newberry, the writers have no information except what is contained in the foregoing quotation, but this evidence may not demonstrate increasing dryness. Perhaps none of the other lines of evidence alone would prove the point, but so many converging lines, all suggesting the same explanation, increase the probability that this is the true explanation.

Geological Evidence of Change of Climate

In geologic literature changes of climate during the past ages have been much discussed, especially, though by no means altogether, in connection with glacial epochs. In the early stages of geologic science it was supposed that there had been a rather uniform cooling of the earth from a molten condition to its present state, with a consequent uniform progressive change of climate from a supposed original warm moist climate to that of the present, with its extremes of temperature and moisture. That supposition was the natural outgrowth of the nebular hypothesis in its earlier form. Gradually accumulating evidence compelled the abandonment of that idea, as it became known that glaciation, desiccation, and other changes of climate had alternated throughout the past ages, instead of there having been progressive change in one direction. The so-called Glacial epoch, for example, was but one of several such epochs extending from Cambrian or pre-Cambrian to Pleistocene time, so that recently it has been well said that "there is no evidence known to the geologist of any progressive refrigeration of the earth." [1] To satisfy the demands of this and of other important facts, the planetesimal hypothesis has been proposed as a modification of or a substitute for the nebular hypothesis.[2] While geologic discoveries indicate that there has been no general progressive change in one direction, it seems settled that there have been repeated fluctuations throughout the past. Perhaps the most radical change of climate was during Pleistocene time, the period which immediately preceded the present, and, indeed, may be considered to extend into and cover the present time. During this period occurred the great Glacial epoch, in which a thick sheet of

[1] Gregory, J. W., Climatic Variations: Their Extent and Causes, in *Smithson. Rep. for 1908*, p. 339, 1909 (address before the Mexico City session of the International Geologic Congress). See also on various climatic changes in the past, among others, the following: Chamberlin, Thomas C., and Salisbury, Rollin D., Geology, I, 643; II, 273, 343, 387, 396, 518, 669; III, 29, 79, 129, 161, 172, 261, 281, 316, 325–515; 1905 and 1906; White, David, and Knowlton, F. H., Evidences of Paleobotany as to Geological Climates, in *Science*, n. s., XXXI, 760, 1910; Reid, H. F., Mr. Manson's Theory of Geological Climates, ibid., XXIX, 27–29, 1909; Coleman, A. P., Glacial Periods and Their Bearing on Geological Theories, ibid., XXVII, 406, 1908; A Lower Huronian Ice Age, ibid., XXV, 769, 1907; Arnold, Ralph, Environment of the Tertiary Faunas of the Pacific Coast of the United States, in *Journ. Geol.*, XVII, 509–33, 1909; White, David, Permo-Carboniferous Climatic Changes in Brazilian South America, as Indicated by Fossil Plants, in *Science*, n. s., XXV, 772, 1907.

[2] Chamberlin, Thomas C., and Salisbury, Rollin D., Geology, II, 38–81, 1906; Chamberlin, Thomas C., A Geologic Forecast of the Future Opportunities of Our Race, in *Science*, n. s., XXX, 938–49, 1909.

ice spread over large portions of Europe, northern Asia, and North America. White and Knowlton say that paleontologically we are still in the Glacial epoch, a period of radical changes. Glacial evidence in the Rocky Mountains also connects the glaciation of the West with the present.

The geologic evidence of a change of climate in the immediate vicinity of the Rito de los Frijoles is very meager or entirely absent. However, when southwestern United States is considered as a whole, there is conclusive evidence of geologically recent widespread change in climate, probably continuing to the present time, which must have affected the area under discussion.

The existence of surface water in its various forms (i. e., as water, ice, and snow) depends not entirely on the amount of precipitation but rather on the relation of precipitation to dissipation. Dissipation may take place by "run-off" through streams, by seepage into soil and rocks, and by evaporation. Evaporation in the Southwest at the present time is a very important factor, vitally affecting both plant and animal life and enormously affecting the culture of the region. It bears a direct relation to the force, continuity, direction, temperature, and humidity of air currents. Hence any influence that would increase or decrease either the temperature or the humidity of atmospheric currents, or change their velocity, continuity, or direction, would manifest itself in the increased or decreased comfort, happiness, and prosperity of the human inhabitants. Precipitation is dependent largely on the distribution of large bodies of land and water and the relation of moisture-laden air currents to such elements of topography as mountains and plains. Hence the causes of regional climates and climatic changes form always a highly complex problem, and though one may determine in many cases from biologic and geologic evidence that changes have occurred in the relation of precipitation to dissipation, it is not so easy to determine whether such changes have affected the one, or the other, or both, or to ascertain the causes of the changes. It may be said that probably in most cases a change in either precipitation or dissipation would react to some extent on the other, so that if there has been progressive desiccation in the Southwest within recent times, it has probably been the result of both decreased precipitation and increased evaporation. The complexity of the problem and the local capriciousness of rainfall, wind, etc., make it difficult or impossible with known methods and few stations to record all the constantly changing factors in such manner as to accurately and adequately plat the curve of the ratio of precipitation to evaporation in a given region. As the existence and extent of land-locked lakes and glaciers are the direct results of this ratio after giving proper value to all factors, the records of their fluctuations, if complete, would furnish the best possible evidence as to

changing climate, taking care to avoid the inference of progressive change in one direction from temporary fluctuation which results from a short cycle of radical climate.

The combined investigations of archeologists and geologists fully demonstrate that a marked though not great change in climate has occurred since primitive man appeared on the earth, a fact so well known that citation of authorities seems scarcely necessary, though a few references may not be out of place.[1]

In Europe man certainly existed during the period of the great continental glaciers, though in America thus far no human remains whose great antiquity is undisputed have been found.[2]

In southwestern United States three lines of geologic evidence may be urged in support of the idea of recent desiccation: the flow of streams, the former existence of lakes where none can now exist, and the former glaciers of the higher mountains.

It has been thought by some geologists that the great canyons of the Southwest must have been cut by much larger volumes of water than now flow through them. Newberry [3] says:

> I use the past participle in speaking of some of the streams whose erosive action has been so marked, from the remarkable fact that many of these eroded valleys are now dry; and in others the present streams are but miniature representatives of those which formerly flowed in their channels. Everything indicates that the table-lands were formerly much better watered than they now are.

Cope [4] says:

> Professor Newberry (Ives' Report) is of the opinion that a diminution in the amount of rain-fall over this region has taken place at no very remote period in the past, and cites the death of forests of pine-trees which still stand as probably due to increasing drought. It is, of course, evident that erosive agencies were once much more active in this region than at present, as the numerous and vast cañons testify, but that any change sufficient to affect this process should have occurred in the human period, seems highly improbable. In other words, the process of cutting cañons of such depth in rocks of such hardness is so slow that its early stages, which were associated with a different distribution of surface-water supply, must have far antedated the human period.

Blake [5] says:

> A change of climatic conditions throughout the Southwest, and especially in the semi-desert region of Arizona and New Mexico, is marked everywhere by the evidence

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[1] Geikie, James, The Great Ice Age and its Relation to the Antiquity of Man; Penck, Albrecht, The Antiquity of Man, in *Science*, n. s., XXIX, 359–60, 1909; Obermaier, Hugues, Quaternary Human Remains in Central Europe, *Smithson. Rep. for 1906*, 373–79, 1907 (reprinted from *L'Anthropologie*); Upham, Warren, The Antiquity of the Races of Mankind, in *Amer. Geol.*, XXVIII, 250–54, 1901; Chamberlin, Thomas C., and Salisbury, Rollin D., Geology, III, 502–16, 1906.

[2] Hrdlička, Aleš, Skeletal Remains Suggesting or Attributed to Early Man in North America, *Bull. 33, Bur. Amer. Ethn.*, p. 98, 1907; Hrdlička *et al.*, Early Man in South America, *Bull. 52, Bur. Amer. Ethn.*, 1912.

[3] Newberry, J. S., Geological Report, in *Report upon the Colorado River of the West, Explored in 1857 and 1858 by Lieutenant Joseph C. Ives*, pt. III, p. 47, 1861.

[4] Cope, E. D., On the Remains of Population Observed On and Near the Eocene Plateau of Northwestern New Mexico, in *Ann. Rep. U. S. Geog. Expl. and Surv. W. of 100th Meridian for 1875*, p. 172, 1875.

[5] Blake, Wm. P., Geological Sketch of the Region of Tucson, Arizona, *Pub. No. 99, Carnegie Inst.*, p. 66, Washington, 1908.

of a much heavier rainfall than we now have. River valleys in many cases show only dry gravelly or sandy beds which evidently were formerly occupied by continuous streams. The floods that once carved their way across the slopes or over the plains are no longer seen, at least not in the same volume as in former time. Even existing streams do not reach in times of great flood their former volume and carrying capacity. All tell of diminished volume, whether in the desert regions or in the regions of abundant plant-growth.

We may not judge of the accuracy of this conclusion without knowing the evidence on which it is based; it is certainly contrary to the opinion of many geologists. Throughout the West and the Southwest are many dry channels which at first give the impression of having once been the beds of perennial streams but which, on careful investigation, seem to have been formed by the intermittent flow of water during wet seasons or after storms. The absence of great floods can not be inferred without very long-continued observation, for extraordinary floods in any region occur scarcely more than once in a generation. There are numerous cases in which destructive floods have visited regions that have been free from them for many years, in a few hours cutting deep channels where none were known before. In many instances the failure of floods to reach former levels results from the deepening of the channels. On this subject Gilbert's remarks[1] are timely:

> As in other desert regions, precipitation here results only from cyclonic disturbance, either broad or local, is extremely irregular, and is often violent. Sooner or later the "cloud-burst" visits every tract, and when it comes, the local drainage-way discharges in a few hours more water than is yielded to it by the ordinary precipitation of many years. The deluge scours out a channel which is far too deep and broad for ordinary needs and which centuries may not suffice to efface. The abundance of these trenches in various stages of obliteration, but all manifestly unsuited to the every-day conditions of the country, has naturally led many to believe that an age of excessive rainfall has but just ceased—an opinion not rarely advanced by travelers in other arid regions. So far as may be judged from the size of the channels draining small catchment basins, the rare, brief, paroxysmal precipitation of the desert is at least equal while it lasts to the rainfall of the fertile plain.

Though for other reasons it seems probable that the flow of streams in this region was at one time much greater than now, the canyons themselves do not necessarily indicate it. It is likely that all the erosion could be accomplished in course of time with no greater volume of water than now flows, and even such canyons as those now without perennial streams could be cut by storm waters, though the work would require more time. However, more rapid cutting by a greater volume of water during the last few thousand years, by shortening the requisite time, would make it easier to understand how the high vertical cliff in the yielding tufa of the Frijoles canyon has been able to stand during the down-cutting period.

[1] Gilbert, G. K., Lake Bonneville, *Monogr. U. S. Geol. Surv.*, 1, 9, 1890.

Still, the cutting of all the canyons long antedated human occupancy of the region, and the streams had probably shrunken much from their former condition before the human invasion.

Geologic evidence leaves no doubt that the Southwest had a climate more humid during part of Pleistocene time than at present. Lakes with outlets do not fluctuate much in depth or area, because during more humid periods the surplus water is carried off by the outlets. Land-locked lakes, on the other hand, vary greatly with fluctuating climatic conditions and constitute an excellent index of those conditions. At present in the Great Basin evaporation bears such ratio to precipitation that no very great lakes are in existence or can exist.[1] It is evident that during part of the Pleistocene period that ratio was different, for then lakes of great size covered portions of the basin and passed through at least two great periods of extension and contraction and probably several minor ones. The best known are Lake Bonneville and Lake Lahontan,[2] though many others are known which are now either dry or occupied only by small shallow saline or alkaline lakes. Lake Bonneville, now represented by the much shrunken Great Salt Lake, then extended over the greater part of what is now western Utah and eastern Idaho and Nevada, with a depth of nearly 1,000 feet at one time. Lake Lahontan, now represented by Humboldt, Pyramid, Carson, Walker, and other small lakes, then covered a large part of what is now northwestern Nevada and extended into California. It is not necessary to suppose that this lake period was one of very great humidity; indeed, it probably was not, otherwise all of the lakes would have overflowed the rims of their basins and established outlets, whereas only part of them succeeded in doing so, and only at the highest stage. However, it is certain that the climate must have been more humid than now. It appears, then, that since late Pleistocene time there has been a change of climate, but the time can not be reckoned in a few years or even a few centuries. The maximum extension of these lakes was many thousand years ago, but their desiccation, with the accompanying minor fluctuations, must have consumed a long period, extending to a much more recent time. Some of the remnants of these ancient lakes have

[1] Davis, Arthur P., The New Inland Sea, in *Nat. Geog. Mag.*, XVIII, 44, 1907; Henry, Alfred J., Salton Sea and the Rainfall of the Southwest, in *Monthly Weather Review*, U. S. Weather Service, XXXIV, 557–59, 1907; *Nat. Geog. Mag.*, XVIII, 245, 1907; Bigelow, Frank H., Studies on the Rate of Evaporation at Reno, Nevada, and in the Salton Sink, ibid., XIX, 23, 1908.

[2] Gilbert, G. K., Contributions to the History of Lake Bonneville, in *Second Ann. Rep. U. S. Geol. Surv., for 1880–81*, pp. 167–200, 1882; Lake Bonneville, *Monogr. U. S. Geol. Surv.*, I, 1890; Russell, Israel C., Sketch of the Geological History of Lake Lahontan, a Quaternary Lake of Northwestern Nevada, in *Third Ann. Rep. U. S. Geol. Surv., for 1881–82*, pp. 189–235, 1883; Geological History of Lake Lahontan, a Quaternary Lake of Northwestern Nevada, *Monogr. U. S. Geol. Surv.*, XI, 1885; A Geological Reconnaissance in Southern Oregon, in *Fourth Ann. Rep. U. S. Geol. Surv., for 1882–83*, pp. 431–64, 1884; Quaternary History of Mono Valley, California, *Eighth Rep., for 1886–87*, pt. I, pp. 261–394, 1889; King, Clarence, Lake Lahontan, in *U. S. Geol. Surv. 40th Parallel*, I, 504–30, 1878.

been observed for many years, particularly Great Salt Lake, which is known to have increased its depth 11 feet and its area 600 square miles from 1867 to 1871.[1] Indeed, the history of the landlocked lakes of the Southwest whose records have been found shows constant fluctuation during the last half century, rather than progressive change in one direction; but any progressive change would be masked by the fluctuations and would be so slow that half a century is not sufficient to show it. The ancient embankments, bars, and other features of the old lake basins are so fresh as to indicate comparatively recent retreat; and if, during a large part of the last 500 or 1,000 centuries, an infinitely slow change has been going on, as indicated by the evidence, there is no reason to suppose that anything has happened to check the desiccation.

At the present time the ratio of precipitation to dissipation is such in the West and the Southwest that glaciers can not exist where they were once abundant. One glacier 7 miles long extended down to an altitude of 9,200 feet in the mountains near Santa Fe and several smaller ones existed there. Not far northward the San Juan and the Sangre de Cristo mountains and nearly the whole crest of the Continental Divide in Colorado were all heavily glaciated. The literature of the subject is very voluminous, but only a few of the more important papers need to be cited.[2] The high sierras in California and the Wasatch Mountains in Utah, together with the mountains of Oregon, Washington, Idaho, Montana, and northward, all had their systems of glaciers. Now no glaciers exist in New Mexico or Utah, only a few very small ones are found in Colorado,[3] while the glaciers of California, Montana, Wyoming, those of nearly the whole of North America, indeed, have shrunken much from their former dimensions. There is no way of knowing just when most of the shrinkage occurred, but the freshness of moraines and of glacial polish and striæ on easily weathered surfaces has convinced nearly all observers that the glaciers of the southern Rockies were extensive at a very late period in the Glacial epoch and that the whole retreat has been geologically recent. This means some thousands of years for the greater part of

[1] See Gilbert's and Russell's monographs, op. cit.; also Powell, J. W., Report on Lands of the Arid Region of the United States, 1879.

[2] See Salisbury, Rollin D., Glacial Work in the Western Mountains in 1901, in *Journ. Geol.*, IX, 718–31, 1901; Stone, George H., Remarks on the Glaciation of the Rocky Mountains, *Monogr. U. S. Geol. Surv.*, XXXIV, 338–54, 1899; Siebenthal, C. E., Notes on Glaciation in the Sangre de Cristo Range, Colorado, in *Journ. Geol.*, XV, 15–22, 1907; Howe, Ernest, and Cross, Whitman, Glacial Phenomena of the San Juan Mountains, Colorado, in *Bull. Geol. Soc. Amer.*, XVII, 251–74, 1906; Hills, R. C., Extinct Glaciers of the San Juan Mountains, Colorado, in *Proc. Colo. Sci. Soc.*, I, 39–46, 1883; *Amer. Journ. Sci.*, 3d ser., XXVII, 391–96, 1884.

[3] See Stone, George H., A Living Glacier on Hague's Peak, Colorado, in *Science*, X, 153–54, 1887; Lee, Willis T., The Glacier of Mt. Arapahoe, Colorado, in *Journ. Geol.*, VIII, 647–51, 1900; Fenneman, N. M., The Arapahoe Glacier in 1902, ibid., X, 839–51, 1902; Siebenthal, C. E., Notes on Glaciation in the Sangre de Cristo Range, Colorado, *Journ. Geol*, XV, 15–22, 1907; Henderson, Junius, Extinct and Existing Glaciers of Colorado, *Univ. Colo. Studies*, VIII, 60–70, 1910.

the recession. It is important to note, however, that most of the glaciers throughout the world which have been observed for any great length of time have retreated during historic times, and most of them are still retreating.[1] As in case of the great lakes of the Southwest, the retreat has not been absolutely continuous but has been interrupted by occasional advances, though on the whole they may be said to have been undergoing the process of retreat during the historic period. The writers' actual observations of Arapahoe glacier in Colorado cover a period of only one decade but show clearly that during that time it has distinctly retreated. Mr. Enos A. Mills states that the same is true of Hallett glacier. The numerous small terminal moraines of Fair glacier indicate that it has been retreating rapidly for some time past. The terminal lakes at the foot of several small glaciers and névé fields in Colorado indicate that they have receded so recently that they have not yet been able to build new terminal moraines, even in case of Arapahoe and Hallet glaciers, which are supplied with abundant morainal material from the cirque walls. All of these facts point with great force to a continued desiccation of the region so near to northern New Mexico, and perhaps also to very widespread desiccation. The same changes which would operate to reduce the glaciers of Colorado would be exceedingly likely to cause desiccation in the vicinity of the Jemez plateau. Of course both temperature and wind affect the melting, and wind and precipitation affect the accumulation of snow, but the most reasonable explanation is that either precipitation has decreased or melting and evaporation have increased (or more likely both), and the effect of either would be desiccation. Actual observation has not been carried on long enough in this region to afford safe evidence, but much safer evidence is found in the present condition of terminal moraines and terminal lakes. Regardless of whether desiccation is now in progress, it seems almost certain that desiccation has been in progress in Colorado during the period of human occupancy of the Southwest and probably in the whole region under consideration. There is no doubt that when the mountains near Santa Fe and northward were glaciated more snow accumulated in the winter in the Jemez Mountains.

Some geologists have supposed that the glaciation of the Rocky Mountains indicates the existence in the past of a colder climate rather than of greater humidity. Careful consideration of the arguments does not convince the writers of the correctness of this view. Just now accumulation and dissipation of snow in the higher portions

[1] See Reid, Harry Fielding, Studies of Muir Glacier, Alaska, in *Nat. Geog. Mag.*, IV, 19–55, 1892; The Variation of Glaciers, in *Journ. Geol.*, III, 269–88, 1895; V, 378–83, 1897; VI, 473–76, 1898; VII, 217–25, 1899; VIII, 154–59, 1900; IX, 250–54, 1901; X, 313–17, 1902; XI, 285–88, 1903; XII, 252–63, 1904; XIII, 313–18, 1905; XIV, 402–10, 1906; XVI, 46–55, 661–68, 1908; XVII, 667–71, 1909; XIX, 83–89, 454–61, 1911; *Science*, N. S. III, 867, 1896; Henderson, Junius, Extinct and Existing Glaciers of Colorado, in *Univ. Colo. Studies*, VIII, 62, 1910.

of the southern Rockies are nearly balanced, the latter being slightly in excess. An increase of a very small percentage in the snowfall would check the waste and a further very slight increase without the least change in mean temperature would cause the glaciers to extend down the canyons. Even an infinitesimal excess of snowfall is sufficient, if time enough be allowed for the accumulation of annual excesses, to produce results. The mean temperature of some of our higher peaks which bear no glaciers is said to be below that of some regions which are supplied with glaciers, a condition which indicates that the thing lacking is precipitation, not low temperature.

It is important to observe that the glaciation of the Rockies was recent as compared with the great Continental glaciers; that the evidence shows very recent retreat, apparently still continuing; that at least the latter part of the Bonneville and Lahontan lake period coincided with the existence of mountain glaciers, as shown by Russell and Gilbert; that both the lakes and the glaciers had two distinct periods of great extension, whose curves coincide in character, these curves having been platted by Russell and Gilbert.

The suggestion long ago made that the desiccation of the region may have been caused by the cutting of the canyons, which established more complete drainage, can not be considered in the present connection, because the canyons were cut almost to their present depth, and thus complete drainage was established, before the construction of the buildings whose ruins form the chief evidence of human occupancy of the region.

The extinction of great mammals, as the mammoth, camel, etc., and the change in the molluscan fauna in the Southwest have also been urged as evidence of desiccation, but these faunal changes have not been very recent compared with the ruins of human habitations; moreover, in case of the mammoth it has become extinct also in regions where there is no particular reason for supposing any marked desiccation has taken place recently.

The distribution of terrestrial mollusks in the Southwest indicates that the intermontane spaces have not been moist enough for migration of land snails during a period of sufficient length for each isolated mountain area to develop its own peculiar forms, especially of such genera as *Sonorella*, *Ashmunella*, and *Oreohelix*.[1] This practical isolation of snails could have resulted, however, even with the precipitation enough greater to permit of raising hardy, drought-resisting varieties of corn with a very small percentage of failures, in many favorable localities where it is not practicable now.

[1] Pilsbry, Henry A., and Ferriss, J. H., Mollusca of the Southwestern States, in *Proc. Acad. Nat. Sci. Phila.*, LVII, 211–90, 1905. See also same publication, LVIII, 123–75, 1908; LXI, 495–518, 1909; especially, LXII, 44–147, 1910 (pp. 46–47).

Aquatic shells and crustacean remains are found in apparently very recent deposits of several small ephemeral lake basins as far north as northern Colorado, under such conditions as to indicate that within perhaps a very few centuries precipitation was sufficient for such forms of life to become established and exist while several feet of fine sediments were accumulating.

Summary

1. The climate of the Rito de los Frijoles and surrounding region does not now permit the raising of corn without irrigation except in perhaps a few favored localities.

2. Climate has fluctuated throughout the geologic ages, though radical changes need not be supposed.

3. It would not require a very great increase in precipitation to make the raising of hardy, drought-resisting varieties of corn possible without irrigation in localities where it is not now possible.

4. Distribution and extent of ruins throughout the Southwest, including the Jemez plateau, strongly suggest different conditions a few centuries ago, with a more general distribution of springs and streams and sufficient precipitation for the cultivation of areas not now fit for agriculture and for the irrigation of tracts where it is now impracticable, thus indicating a probable change of climate within at most the last ten to twenty centuries. There is some direct historical evidence pointing the same way.

5. The former existence of extensive lakes where the ratio of evaporation to precipitation does not now permit them indicates change of climate within a few thousand years, leaving the question open as to whether the change was still in progress during the human occupancy of the area dealt with in this paper.

6. The disappearance of nearly all glaciers from the southern Rockies, including those which existed within a short distance of the Jemez plateau, and the very recent recession of those which remain, together with the fact that they appear to be still receding, indicate a change in climate since a very late period in the Glacial epoch and that probably the change is still in progress.

7. There is some botanical evidence, although meager, of a change in climate within four or five centuries and of the still-continuing desiccation.

8. On the whole, in the opinion of the writers, various lines of evidence point to progressive desiccation of the region since the beginning of the pueblo and cliff-dwelling period, with no important evidence inconsistent with this view, although the change in population may possibly be ascribed to other causes.

9. This progressive desiccation, if it has occurred, doubtless has been accompanied by numerous slight fluctuations in climatic conditions, just such as are matters of record during historic time, wet and dry and warm and cool cycles alternating.

10. Any such progressive change would necessarily be infinitely slow, so that it would not be shown by meteorologic records unless continued through many centuries, with very delicate observations at many stations throughout a large area.

11. A natural result of such slow desiccation would be the gradual reduction of the population and the concentration of the remnants in favorable localities. Its effect on the native vegetation would be chiefly in the direction of changing somewhat the boundaries of the plant formations. Its effect on the fauna could not be readily detected except by the discovery of numerous fossils of recent date or by the inferential evidence that might be derived from careful study of the distribution of forms which can not readily migrate over unfavorable areas.

12. Evidence of recent desiccation is not conclusive, but the problem is probably capable of solution by further cooperative investigation along lines suggested in this discussion. Several lines of evidence point to slight progressive desiccation in the Southwest within the period of human occupancy. Such desiccation would satisfactorily account for present conditions, and no other explanation yet suggested seems adequate.

Suggestions for Future Work

The foregoing summary suggests lines of work for the future, as—

1. Keeping accurate records for a long period at numerous stations, of direction, continuity, and force of prevailing winds, temperature, evaporation, and relative humidity.

2. A thorough study of the ruins and of human remains to ascertain, if possible, what proportion were occupied simultaneously or abandoned simultaneously, whether abandoned suddenly, and whether general or continued warfare, pestilence, or earthquakes may have aided in the depopulation of the region.

3. The more complete investigation of the definite traditions of the peoples regarding former climatic and agricultural conditions, without unconsciously suggesting to them the answers to inquiries. Also a careful study of old Spanish records and literature of the region with this question in mind.

4. The careful recording of the fluctuations of land-locked lakes and of the flow of streams, carried on from generation to generation.

5. Systematic records of the changes in area, depth, and outlines of glacier remnants, névé and so-called banks of perpetual snow, including also the time of disappearance in summer of large banks of snow which do not remain throughout the year but appear at the same points year after year in the winter. A convenient and safe method of obtaining these records is to photograph each of these fields of snow and ice from the same point on the same day of successive years.

6. Botanical evidence offers a most promising and little exploited field, especially the investigation of the extension or contraction of forest areas, the relations of large plant formations to one another, and the extent to which trees are dying and the causes of this condition.

7. The existence of botanical "islands" of certain vegetation of types left in favorable situations as the climate became unsuited for their general distribution and peculiar adaptations of various types of plants to meet changing conditions would also be important discoveries.

8. An exhaustive study of the distribution of living and recently extinct faunas, especially forms which do not migrate readily, would doubtless furnish valuable evidence.

9. A search for ancient springs, irrigation works, reservoirs, and garden or farming plots in localities now far from water.

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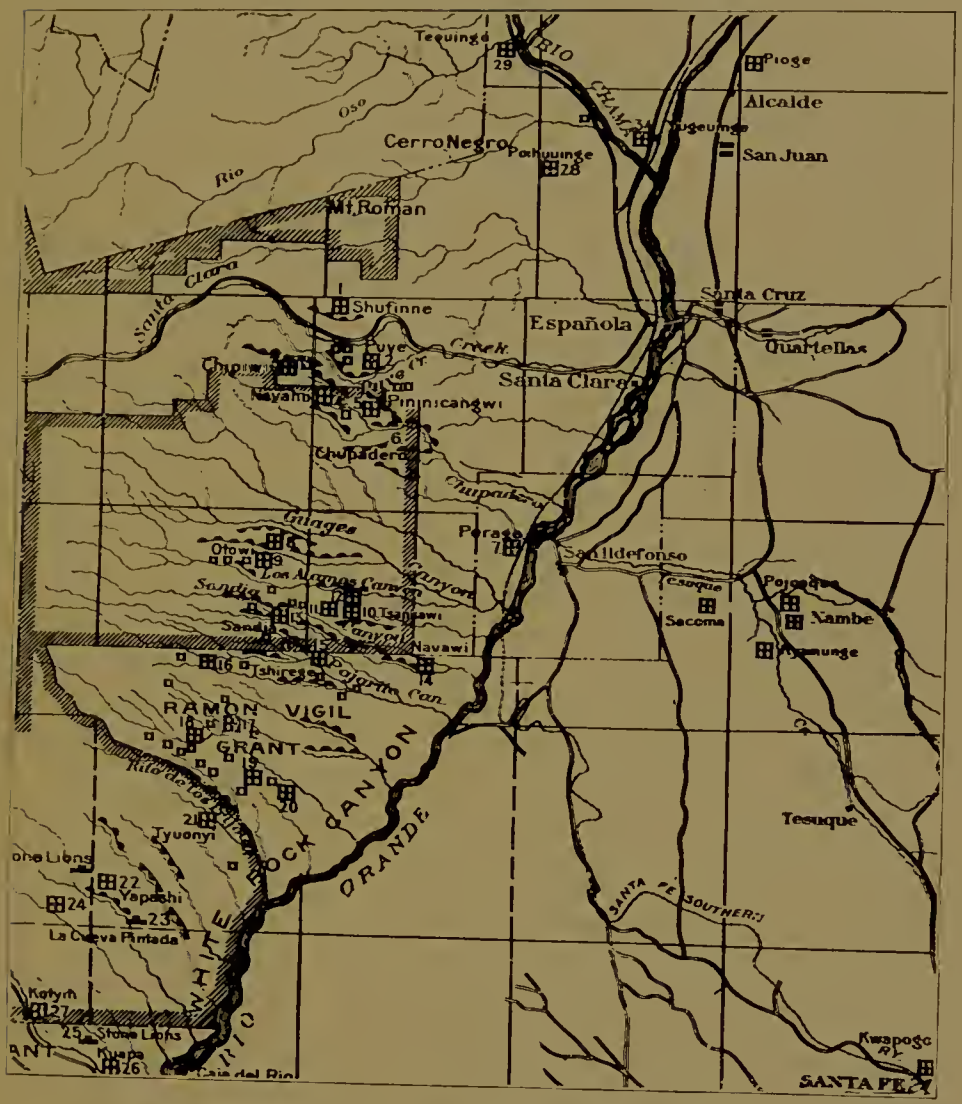

ARCHEOLOGICAL MAP OF A PART OF THE PAJARITO PLATEAU